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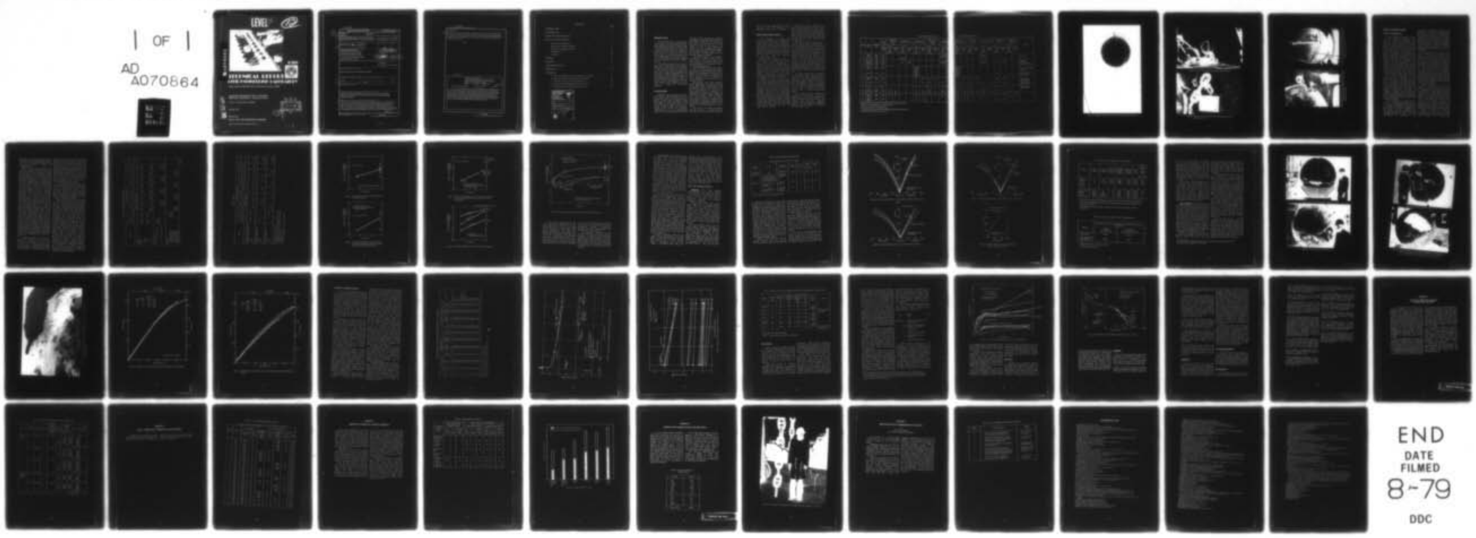

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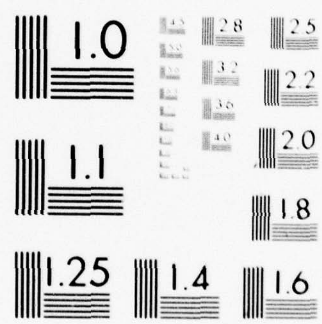

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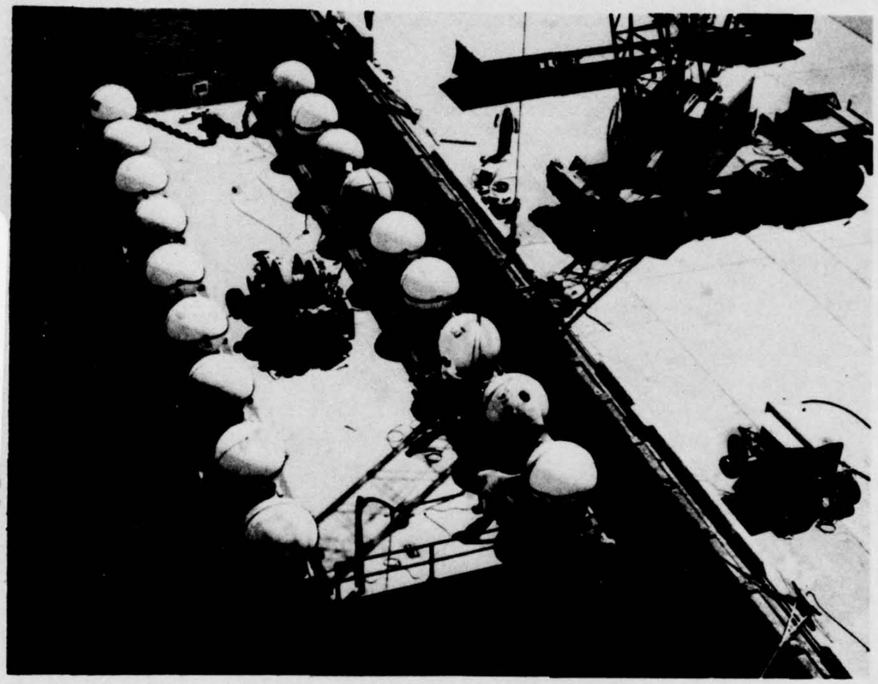

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TECHNICAL REPORT
CIVIL ENGINEERING LABORATORY

Naval Construction Battalion Center, Port Hueneme, California 93043

LONG-TERM, DEEP-OCEAN TEST OF CONCRETE SPHERICAL STRUCTURES – Results After 6 Years

By Harvey H. Haynes and Roy S. Highberg

January 1979

Sponsored by
NAVAL FACILITIES ENGINEERING COMMAND

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

14

1. REPORT NUMBER
CEL-TR-869

2. GOVT ACCESSION NO.
DN044053

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
6 LONG-TERM, DEEP-OCEAN TEST OF CONCRETE SPHERICAL STRUCTURES – Results After 6 Years.

5. TYPE OF REPORT & PERIOD COVERED
Not final; Jul 1971 – Mar 1978

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
10 Harvey H. Haynes [redacted] Roy S. Highberg

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Civil Engineering Laboratory
Naval Construction Battalion Center
Port Hueneme, California 93043

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
16 17
63713N, S0397, S0397-SL
3.1610-1

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Facilities Engineering Command
Alexandria, Virginia 22332

12. REPORT DATE
11 Jan[redacted]979 12 53p.

13. NUMBER OF PAGES
51

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

9 Final rept Jul 71 – Mar 78,

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Concrete structures, pressure-resistant structures, concrete spheres, permeability, implosion, submerged concrete structures, undersea structures, long-term loading, unreinforced concrete.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In 1971, a long-term, deep-ocean test was started on eighteen concrete spheres, 66 inches (1,676 mm) in outside diameter by 4.12 inches (105 mm) in wall thickness. The spheres were placed in the ocean at depths from 1,840 to 5,075 feet (560 to 1,547 m). Over a 6.4-year period, yearly inspections of the spheres by submersibles have provided data on time-dependent failure and permeability. After 5.3 years, three of the spheres were

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

391 111

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retrieved from the ocean for laboratory testing. Data on concrete compressive strength gain, short-term implosion strength of the three retrieved spheres, and permeability and durability of the concrete were obtained. This report summarizes the findings from the laboratory and ocean tests.

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Civil Engineering Laboratory
LONG-TERM, DEEP-OCEAN TEST OF CONCRETE SPHERICAL STRUCTURES – Results After 6 Years, by Harvey H. Haynes and Roy S. Highberg
TR-869 51 pp illus January 1979 Unclassified

1. Undersea concrete structures 2. Concrete spheres I. 3.1610-1

In 1971, a long-term, deep-ocean test was started on eighteen concrete spheres, 66 inches (1,676 mm) in outside diameter by 4.12 inches (105 mm) in wall thickness. The spheres were placed in the ocean at depths from 1,840 to 5,075 feet (560 to 1,547 m). Over a 6.4-year period, yearly inspections of the spheres by submersibles have provided data on time-dependent failure and permeability. After 5.3 years, three of the spheres were retrieved from the ocean for laboratory testing. Data on concrete compressive strength gain, short-term implosion strength of the three retrieved spheres, and permeability and durability of the concrete were obtained. This report summarizes the findings from the laboratory and ocean tests.

CONTENTS

INTRODUCTION

In September 1971, a test program was started on concrete spherical structures placed in the deep ocean for long-term testing. This report is the second in a series documenting the study; presented are the test results of the spheres after 6.4 years in the ocean. The first report (Ref 1) covered the fabrication, ocean emplacement, and inspections up to 1.3 years. Details of the test program and the specimens are given in Reference 1.

The technical objectives of the program are to obtain data on time-dependent failure, permeability, and durability of the concrete spherical structures. These data can provide a technology base from which engineering guidelines could be written. Another important aspect of the program was to expose the spheres to real environmental conditions. The test results will aid considerably in establishing confidence and credibility for concrete as a deep-ocean construction material.

BACKGROUND

Eighteen concrete spheres 66 inches (1676 mm) in outside diameter and 4.12 inches (105 mm) in wall thickness were placed in the ocean at depths varying from 1,840 to 5,075 feet (560 to 1,547 m). Sixteen of the spheres were unreinforced concrete, eight of which were coated on the exterior with a phenolic compound to act as a waterproofing agent; the other eight spheres were left uncoated. The remaining two spheres were lightly reinforced with 0.5-inch (13-mm) diameter steel bars. The reinforcing bars had a concrete cover of 1 and 2.5 inches (25 and 63 mm). Half of the exterior of each of these spheres was coated with the waterproofing agent. The reinforced spheres were to determine whether corrosion problems exist in the deep ocean environment.

The depth range for the spheres corresponds to relative load levels of from 0.36 to 0.83. The relative load level, P_s/P_{im}^p, is defined as the ratio of sustained pressure to predicted short-term implosion pressure.

Time-dependent failure was expected for six of the spheres subjected to the highest load levels; therefore, those spheres were equipped with clock mechanisms to record the day of implosion. If other specimens were to implode, the yearly inspections would discover the failed specimens.

Permeability data were gathered during inspections. The spheres, which were approximately 1,000 pounds (450 kg) buoyant, were tethered 30 feet (10 m) off the seafloor by a 2.25-inch (57-mm) diameter chain. As seawater was absorbed by and permeated through the concrete, the sphere weight increased. The reduced buoyancy of the sphere meant that less chain was suspended off the seafloor. Therefore, change of one chain link corresponded to 0.50 cu ft (14 liters) of seawater being taken on by the sphere.

The concrete mix design was Type II Portland cement, a water-to-cement ratio of 0.41, a sand-to-cement ratio of

1.85, and a coarse-aggregate-to-cement ratio of 2.28. The maximum size aggregate used was 3/4 inch (19 mm).

INSPECTION AND RETRIEVAL

The operations to inspect and retrieve the spheres were conducted by submersibles. The Navy's deep-diving manned submersibles Turtle and Seacliff, operated by the Submarine Development Group One, were used in all but one operation; Scripps Institution of Oceanography used their Remote Underwater Manipulator (RUM) to conduct an inspection in 1972. The last inspection occurred in March 1978.

During each operation, only a limited number of spheres were inspected. Those checked depended on the number of dive days scheduled for the submersible and on weather conditions, which could restrict the actual number of dives. Hence, some spheres have been inspected more frequently than others (Figure 1). Sphere no. 6 has not been inspected as yet. Table 1 summarizes the data obtained during the inspections.

Spheres no. 15 and 17 show chain link counts (the number of links suspended off the seafloor) that increased with time in the ocean. This increase in chain link count was due to inaccuracies in counting links. Turbidity sometimes obscured the links near the seafloor, making it difficult for the submersible operators to get an accurate count. Also, the submersible operators were changed with each dive, which caused variations in the data collection procedure. More reliable data have been obtained during recent inspections because chain link counts were sometimes taken two and three times as a check.

During the sixth inspection in January 1977, Spheres No. 11, 12, and 13 were recovered after 5.3 years in the ocean. Two of the spheres had a waterproof coating and were retrieved from depths of 2,635 and 3,140 feet (803 and 957 m). The other sphere was uncoated and was retrieved from a depth of 2,790 feet (851 m).

The submersible Seacliff made a separate dive to retrieve each sphere. A reel containing 6,000 feet (2,000 m) of 1/2-inch (13-mm) nylon line was attached to the front end of the submersible. A large steel hook was connected on the end of the line. Using a manipulator, the Seacliff attached the hook to the Sphere's tether chain and then payed-out the line as it surfaced. At the water surface, the line was buoyed with a marker. The CEL warping tug was then employed to reel in the line and recover the sphere (Figure 2). Each sphere was subsequently wrapped in wet burlap and plastic sheet to prevent it from drying out.

A surface inspection of the spheres revealed tube worms and a grass-like animal growth on the coated spheres as well as a few small anemones and a grouping of small scallops. The concrete surfaces, whether coated or uncoated, had considerably less grass-like growth than the steel chains (Figure 3). Figures 4 and 5 show a close-up view of the exteriors for a coated and uncoated sphere.

These spheres were subsequently tested in the laboratory where they provided data on the actual quantity of water permeating to the inside of the spheres, the short-term implosion pressure and strain behavior of preloaded spheres, and the chemical compounds present in the concrete.

Table 1. Sphere Inspection Data

Sphere No.	Exterior Surface	Emplacement Depth (ft)	No. of Chain Links Off Seafloor at Start of Test[a]	Inspection No. 1 (Mar 1972, 163 days)		Inspection No. 2 (Aug 1972, 340 days)		Inspection No. 3 (Dec 1972, 431 days)		Inspection No. 4 (Nov 1973, 776 days)		Inspection N (Oct 1974, 1,1	
				No. of Chain Links Off Seafloor	Permeated Water[b] (ft^3)	No. of Chain Links Off Seafloor	Permeated Water (ft^3)	No. of Chain Links Off Seafloor	Permeated Water (ft^3)	No. of Chain Links Off Seafloor	Permeated Water (ft^3)	No. of Chain Links Off Seafloor	Pe
1	Coated	5,075	29.7									Imploded	
2	Coated	4,875	29.7									No count*	
3	Coated	4,330	29.4			Imploded							
4	Uncoated	4,185	29.4			23	0.99					No count*	
5	Uncoated	4,100	29.6			21	2.06					No count*	
6	Uncoated	3,875	29.6										
7	Coated	3,725	31.5					Imploded					
8	Coated	3,665	31.5					Intact, but on bottom*					
9	Uncoated	3,295	31.6					Chain tangled*					
10	Uncoated	3,190	31.6					24	1.58	24	1.58		
11	Coated	3,140	34[c]					31	0	31	0		
12	Uncoated	2,790	31.7[d]					24	1.63	24.5	1.38	24.5	
13	Coated	2,635	32.1					29	0	29	0	29	
14	Coated	2,440	43[c]	39	0			39	0	38.5	0	38.25	
15	Uncoated	2,300	32.2	26	0.89			25	1.38	25.5	1.14	25.75	
16	Uncoated	2,120	31.8	26	0.70			25	1.19	25	1.19	24	
17	Half-coated	1,980	32.6	29	0			28	0			29	
18	Half-coated	1,840	32.6					25	1.28				

[a]Original number of links off seafloor calculated from known weights of components.

[b]Based on 3% by weight absorption to saturate the concrete.

[c]New chain count based on retrieved sphere data.

[d]Extra shackle found on retrieved chain which changed number of links from Reference 1.

[e]Actual quantity of permeated water was 1.24 ft^3.

Table 1. Sphere Inspection Data

Inspection No. 3 (Dec 1972, 431 days)		Inspection No. 4 (Nov 1973, 776 days)		Inspection No. 5 (Oct 1974, 1,120 days)		Inspection No. 6 (Jan 1977, 1,945 days)		Inspection No. 7 (Mar 1978, 2,355 days)		Comments
No. of Chain Links Off Seafloor	Permeated Water (ft^3)	No. of Chain Links Off Seafloor	Permeated Water (ft^3)	No. of Chain Links Off Seafloor	Permeated Water (ft^3)	No. of Chain Links Off Seafloor	Permeated Water (ft^3)	No. of Chain Links Off Seafloor	Permeated Water (ft^3)	
				Imploded No count*		27	0			*Sphere intact
				No count*		14	5.38			*Sphere intact
				No count*		18	3.53			*Sphere intact
										Not inspected to date
Imploded										
Intact, but on bottom*										*Sphere flooded, probably from leak
Chain tangled*						Intact				*Chain tangled; could not count links
24	1.58	24	1.58			23	2.06			
31	0	31	0			30.5*	0			*Retrieved during Inspection No. 6
24	1.63	24.5	1.38	24.5	1.38	24.5*	1.38			*Retrieved during Inspection No. 6[c]
29	0	29	0	29	0	29*	0			*Retrieved during Inspection No. 6
39	0	38.5	0	38.25	0	38	0			
25	1.38	25.5	1.14	25.75	1.02	25	1.38	25.75	1.02	
25	1.19	25	1.19	24	1.67	23	2.16	22	2.64	
28	0			29	0			29	0	
25	1.28					21	2.91			

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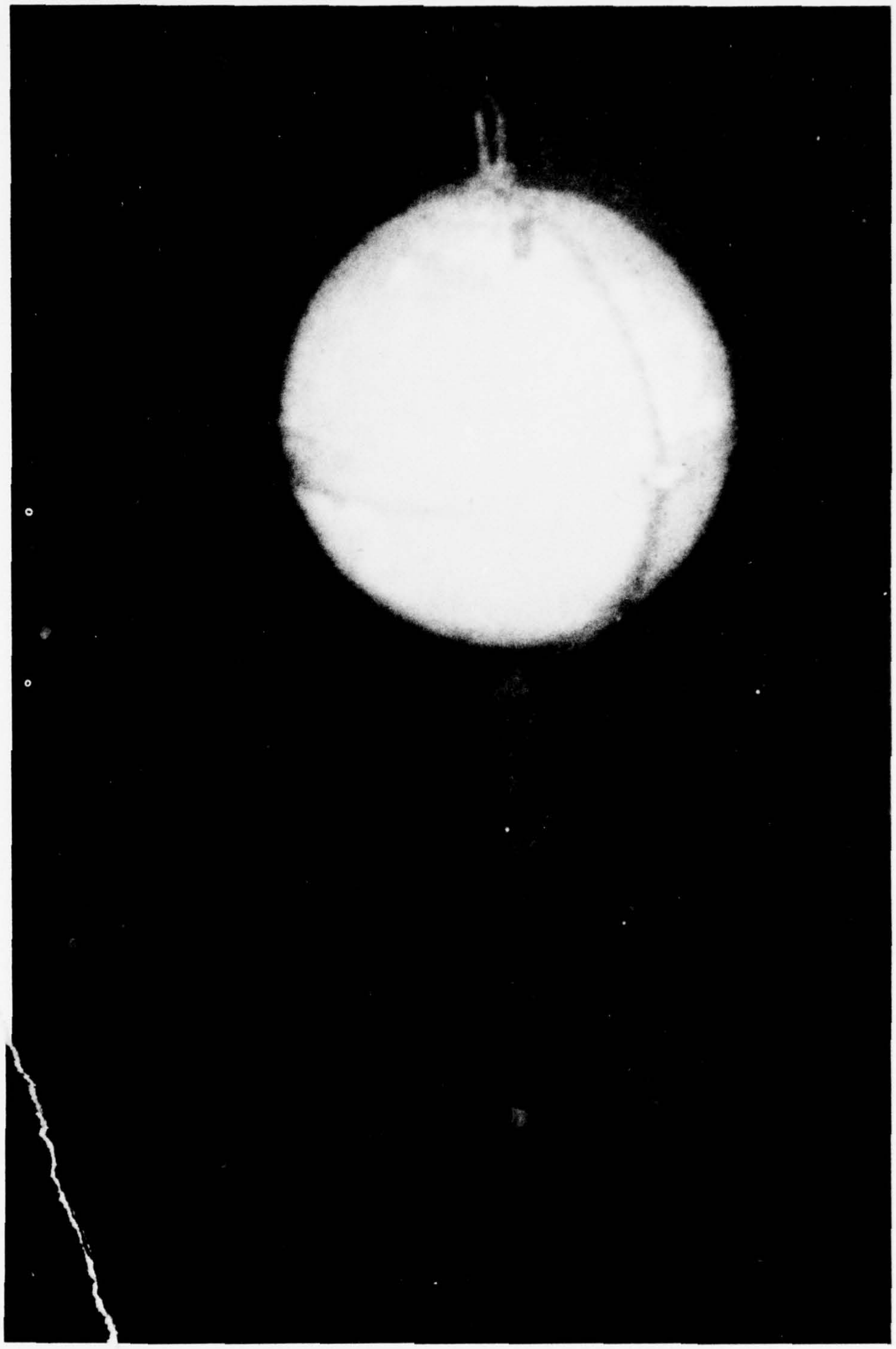

Figure 1. Sphere no. 12 shown after 1 year in the ocean at 2,790 feet (850 m).

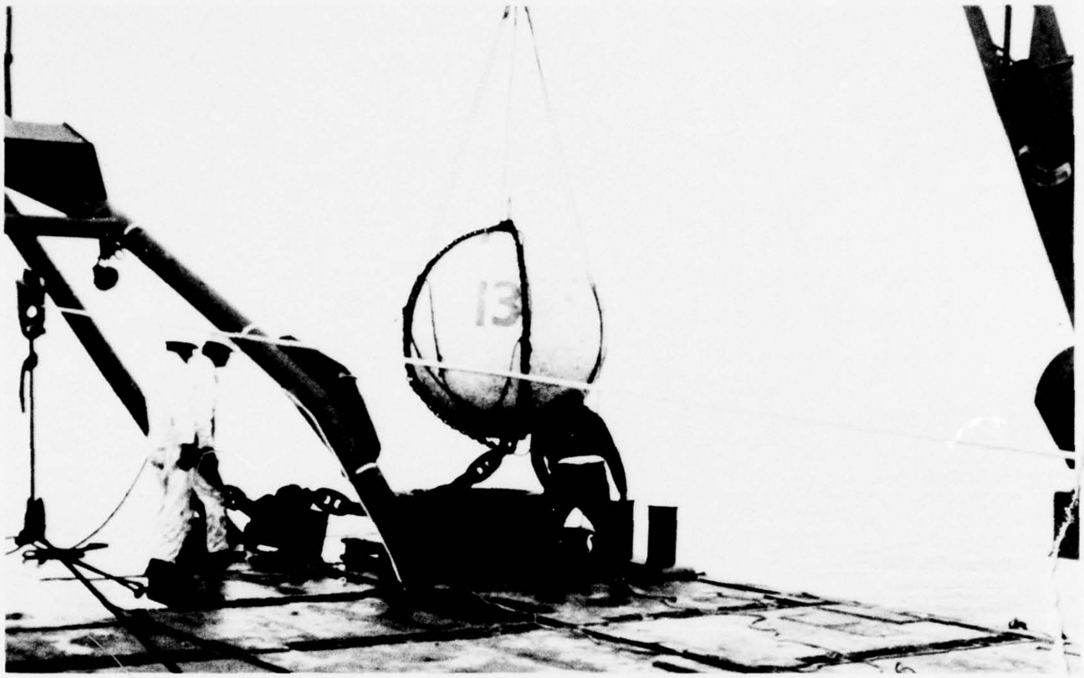

Figure 2. Sphere no. 13 retrieved from depth of 2,635 feet (803 m).

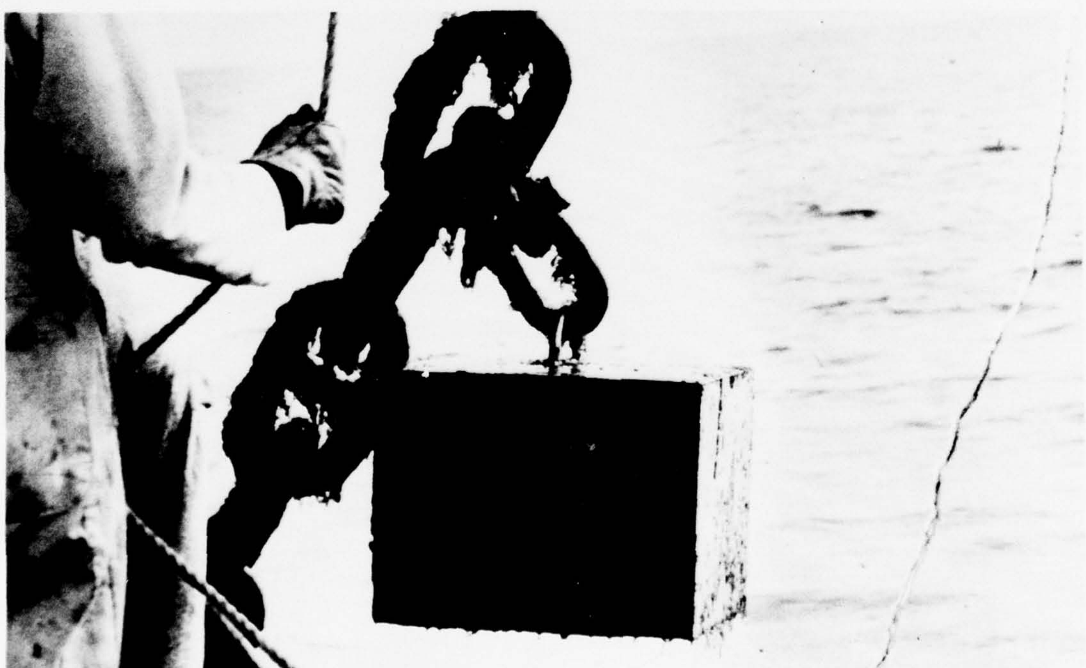

Figure 3. Uncoated concrete block had considerably less grass-like gr owth than the steel chain.

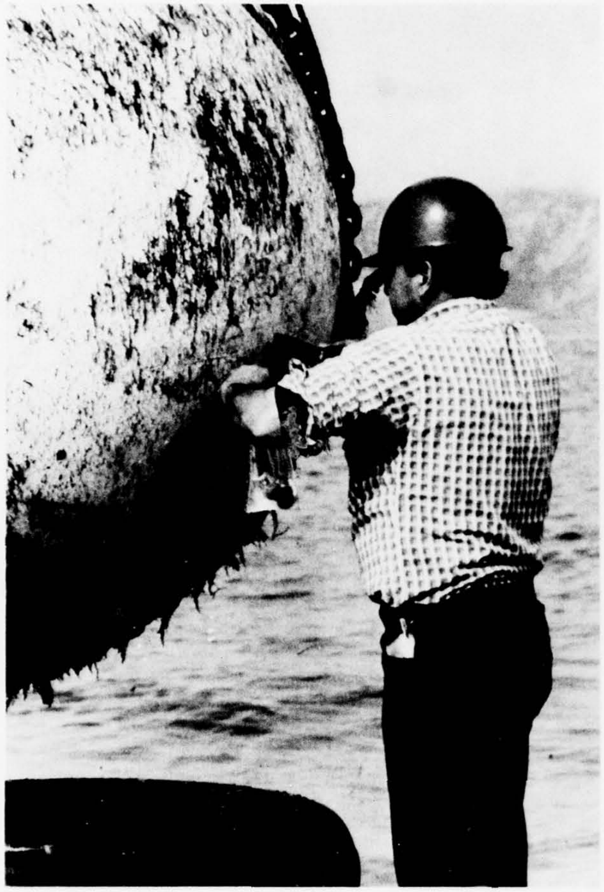

Figure 4. Sphere no. 13 was a coated sphere, which made the grass-like growth more visible. A technician is collecting scallop samples.

Figure 5. Sphere no. 12 was an uncoated sphere, which made the tubeworms more visible. The grass-like growth is visible on the white numerals.

RESULTS AND DISCUSSION

Concrete Strength Gain

The compressive strength of concrete after curing in the ocean for 1.3 and 5.3 years was obtained from uncoated concrete blocks that were attached to the chain of the spheres (Figure 3). The block size was 14 x 18 x 18 inches (356 x 457 x 457 mm), from which four 6 x 12-inch (152 x 305-mm) cores were drilled. The uniaxial compressive strength of the cores was compared to that of 6 x 12-inch (152 x 305-mm) cast cylinders made from the same batch of concrete and cured under continuous fog room conditions. The strength was also compared to that of on-land cured concrete blocks located about 150 feet (50 m) from the shoreline. These blocks were the same size as those in the ocean, and test specimens were cored from the blocks. The compressive strength results are presented in Table 2.

A strength differential has been observed to occur between cast and cored specimens of the same concrete due to the effect of drilling. The compressive strength of the core specimens in this study was increased by 7% so that it would be equivalent to that of the cast specimens. (Past data supporting the strength adjustment are given in Appendix A). Table 2 presents both the measured strength of the core specimens and the adjusted strength. The following analysis of strength data is based on the adjusted strengths.

The compressive strength gain of concrete in the different curing environments is presented graphically in Figures 6 through 9. Relative strengths are shown where the common denominator is the 28-day fog-cured strength. This strength had a nominal value of 8,000 psi (55 MPa). Reference 1 did not give the coefficients of variation of the compressive strengths for spheres at 28 days and at the time of emplacement; these data are now given in Appendix B. At 5.6 years of age, the continuously fog-cured concrete showed a relative strength of 1.35 (coefficient of variation was 5.2%). The on-land field-cured concrete showed a relative strength of 1.32 (coefficient of variation was 8.0%), and the ocean-cured concrete a relative strength of 1.15 (coefficient of variation was 9.5%).

The data from the on-land field-cured concrete are interesting but difficult to discuss because the concrete's actual moisture content varied with time. The compressive strength of dry concrete is greater than that of equivalent wet concrete by an average of 20% (Ref 2, 3). The degree of dryness, i.e., the relative humidity of the environment with which concrete is in equilibrium, also influences the compressive strength. For our case, the equilibrium relative humidity was not known. At 5.6 years, spring was starting after a drought year. However, because of the proximity of the concrete blocks to the ocean, the environmental relative humidity was high (100%) most evenings.

Samples were dried in an oven to obtain an indication of how much absorbed water the on-land concrete had in comparison to the fog- and ocean-cured concrete. These data are given in Appendix C. As expected, the on-land concrete contained less moisture than either the fog-cured or ocean-cured concrete. It is likely that if the on-land concrete were soaked in water for several days prior to uniaxial testing, the compressive strength would have decreased. The amount of the decreases would have been an estimated 5 to 15%.

Figure 10 shows a constructed relationship between relative strength and total age for the fog- and ocean-cured concrete. The strength gain

behavior for the fog-cured concrete is consistent with existing knowledge. However, the strength gain behavior for the ocean-cured concrete is unusual and needs discussion.

When a mass of concrete the size of a control cylinder is placed in the ocean under high hydrostatic pressure, water fills the larger size voids within a period of several days. The smaller size voids become filled over a much longer time period. For example, 6 x 12-inch (152 x 305-mm) cylinders under a pressure head of 550 feet (168 m) were still absorbing water after 84 days (Ref 4). Saturated concrete, that is, concrete whose voids are mostly filled with water, has been found previously to have a strength reduction of 10% compared to companion unsaturated concrete. This strength reduction was observed from two different types of tests: (1) specimens were exposed to a pressure head of 1,125 feet (343 m) for 7 days and then tested under uniaxial compression in a laboratory environment (Ref 1, 5); and (2) specimens were placed under a pressure head of 20,000 feet (6,096 m) for 60 days and then loaded axially while in the hydrostatic environment (if the concrete was totally saturated, which was the assumed condition, then this test was a uniaxial compression test) (Ref 4). The cause of these strength reductions was most likely from pore pressure buildup. During uniaxial loading, the water pressure in some of the pores rose slightly, thereby placing an additional component of tensile strain within the specimen that reduced the tensile strength in the radial direction and, consequently, reduced the compressive strength in the axial direction.

In Figure 10, when concrete specimens were placed in the ocean, a decrease in strength of about 10% occurred. At 1.6 years, ocean-cured concrete showed a compressive strength that was still less than the 28-day fog-cured strength. Two alternative paths are shown in estimating the relationship between the time the concrete was placed in the ocean and 1.6 years. For the lower path, which intersects the datum point at 1.6 years, the initial strength reduction when placed in the ocean had to be greater than 10%. The higher path assumes that the data at time 0.25 years to be accurate and those at 1.6 years to be a "low" result. The data at 1.6 years are from one concrete block, producing four cores with a coefficient of variation of 4.0%.

At 5.6 years, the cement was completely hydrated for both the fog-cured and ocean-cured concrete as determined from x-ray diffraction analysis of the concrete. Hence, the rate of strength gain of the concrete, or the slope of the curve, should be zero. However, strength changes could be occurring due to other chemical composition changes.

Also, at 5.6 years, the ocean-cured concrete showed a compressive strength 15% less than that of the fog-cured concrete. This strength reduction had to be due to a different reason than saturation effect because at this advanced age, both the fog- and ocean-cured concretes are known to be saturated (Ref 4). Therefore, the cause for the lower strength of the ocean-cured concrete as compared to the fog-cured concrete can be speculated as mainly due to the presence of seawater. Magnesium ions in seawater replace some of the calcium ions in calcium silicate hydrate (tobormorite gel). This causes the formation of magnesium silicate hydrate, which is more brittle than calcium silicate hydrate (Ref 6). Specimens of pure cement paste are required in order to determine the presence of magnesium silicate hydrate with a scanning electron microscope. Hence, these concrete samples could not be tested for magnesium silicate hydrate. Appendix D presents an extension to the sphere program which will provide data so that the phenomenon of magnesium ions replacing calcium ions can be studied.

Table 2. Compressive Strength Test Results

Parameter	Concrete Used in Sphere —										Average
	No. 3		No. 11		No. 12		No. 13		No. 1		
	W-15[a]	W-16	W-24	W-21	W-32	W-29	W-26	W-23	W-4	W-35	
Compressive Strength, f'_c (psi)											
Fog cure[b]											
28-day	8,520 (1.5%)[d]	8,400 (1.9%)	7,540 (3.8%)	7,720 (2.7%)	7,570 (0.6%)	7,240 (3.0%)	8,070 (4.5%)	7,640 (2.0%)	8,520 (0.1%)	8,070 (2.1%)	–
Total age											
1.3 yr	10,470 (3.9%)	10,360 (1.5%)									–
5.6 yr			10,960 (3.3%)	10,710 (2.1%)	10,210 (4.2%)	10,160 (2.8%)	10,950 (3.2%)	10,220 (9.6%)	10,410 (3.6%)	10,430 (2.4%)	–
On-land field cure[c]											
1.3 yr (includes 28-day fog cure)	9,260 (8,650[e] 3.7%)										–
5.6 yr (includes 28-day fog cure)				9,200 (8,600 2.0%)		10,370 (9,690 2.9%)		9,760 (9,120 1.0%)		11,090 (10,360 3.1%)	–
Ocean cure[c]											
1.3 yr (includes fog cure, on-land field cure, and 341 days submerged)		8,130 (7,600 4.0%)									
5.6 yr (includes fog cure, on-land field cure, and 1,950 days submerged)			8,320 (7,780 3.9%)		9,960 (9,310 1.9%)		9,060 8,470 0.4%		9,150 (8,550 1.9%)		–

continued

Table 2. Continued

Parameter	Concrete Used in Sphere --										Average
	No. 3		No. 11		No. 12		No. 13		No. 1		
	W-15[a]	W-16	W-24	W-21	W-32	W-29	W-26	W-23	W-4	W-35	
Relative Strength											
Total-Age fog cure/28-day fog cure											
1.3 yr	1.229	1.233									
5.6 yr			1.454	1.387	1.349	1.403	1.357	1.338	1.222	1.292	1.350 (5.2%)
On-land cure/28-day fog cure											
1.3 yr	1.087										
5.6 yr				1.192		1.432		1.277		1.374	1.319 (8.0%)
Ocean cure/28-day fog cure											
1.3 yr		0.968									
5.6 yr			1.103		1.316		1.123		1.074		1.154 (9.5%)

[a]Hemisphere section identification.

[b]Average of three 6 x 12-inch (152 x 305-mm) cast cylinders.

[c]Average of four 6 x 12-inch (152 x 305-mm) core specimens.

[d]Coefficient of variation.

[e]Unadjusted core strength with coefficient of variation.

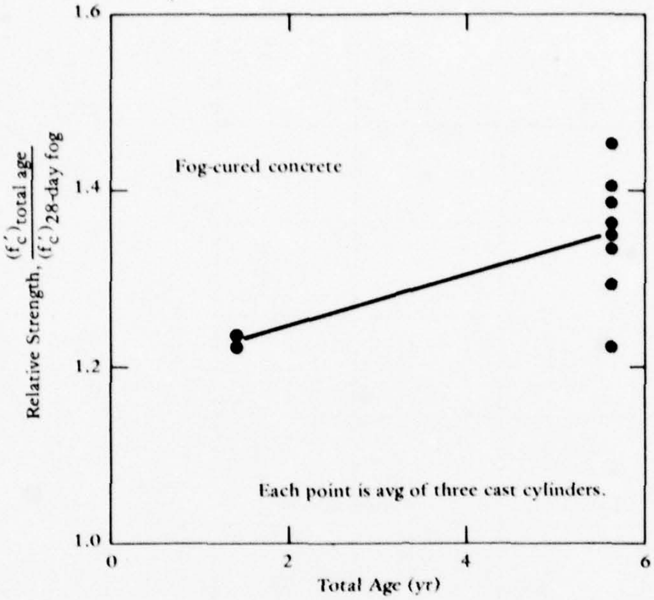

Figure 6. Compressive strength gain of concrete exposed to continuous fog curing.

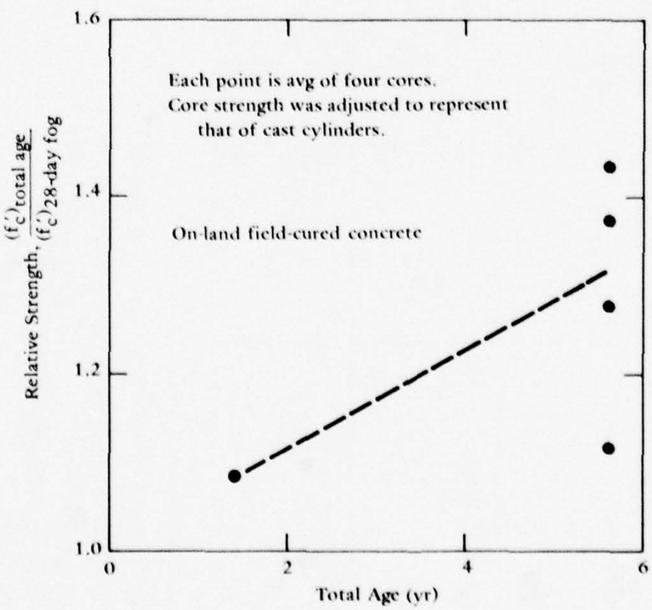

Figure 7. Compressive strength gain of concrete exposed to on-land field curing after initial 28-day fog curing. Location was about 150 feet from ocean.

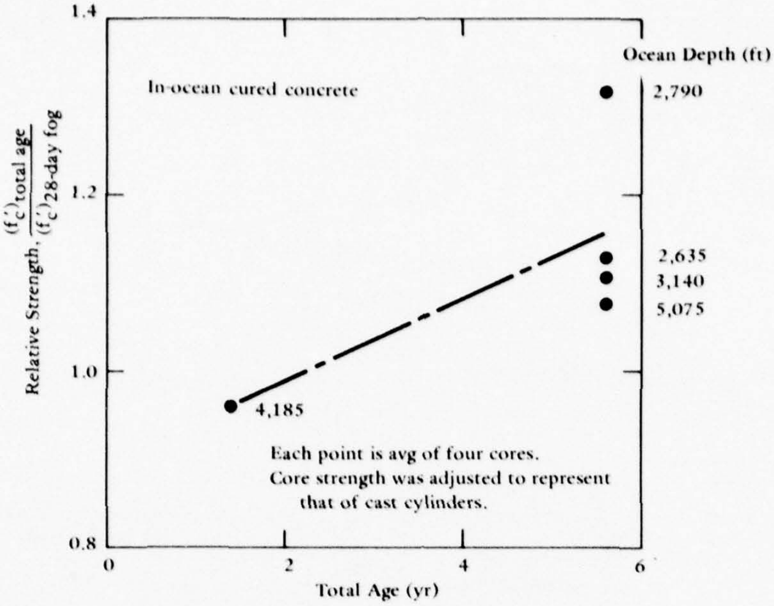

Figure 8. Compressive strength gain of concrete exposed to ocean curing conditions after initial 28-day fog cure and 2 to 5 months of on-land curing.

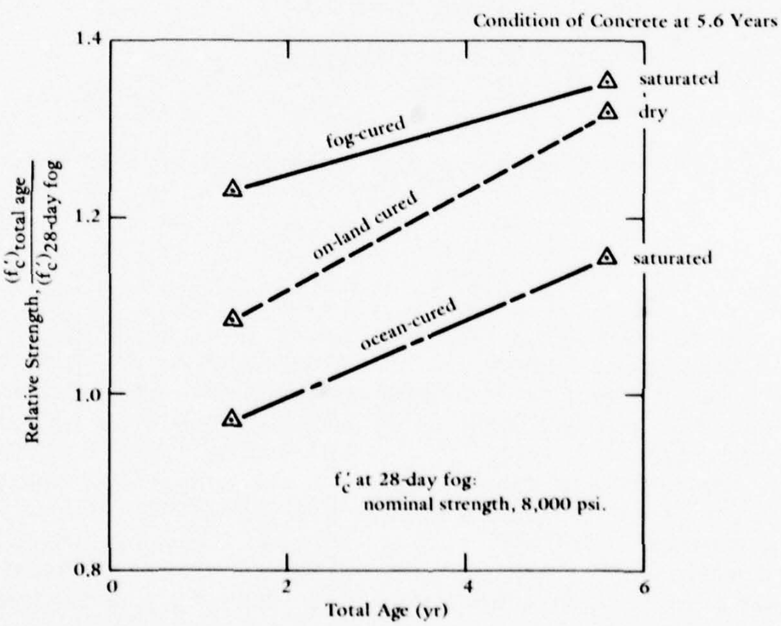

Figure 9. Compressive strength gain of concrete in different environments.

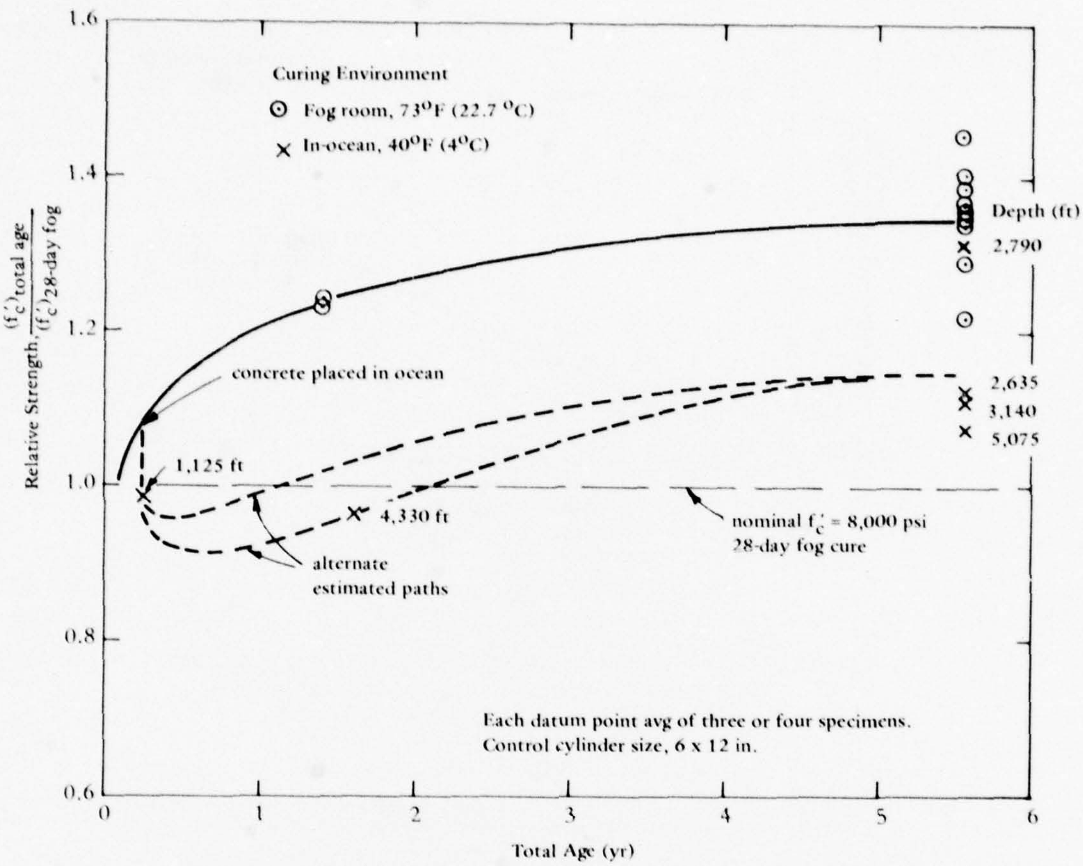

Figure 10. Relative compressive strength of fog-cured and ocean-cured concrete.

It can also be speculated that the cold temperature environment of the ocean had a small effect on retarding full development of strength gain. The ocean temperature was 40F (4C), whereas the fog room environment was 73F (22.8C). Discussion of the long-term effect of a continuous 40F (4C) curing environment was not found in the literature. Lorman (Ref 7) gave limited test results on concrete that set and cured under seawater at 47F (8.3C) compared to that in a 73F (22.8C) fog environment. After 28 days, the concrete in the cold environment showed a compressive strength that was approximately 10% less than the control concrete.

The important findings from the data are: (1) the ocean-cured concrete required 1 to 2 years in the ocean before regaining a strength equal to its 28-day fog strength; and (2) within the time period of up to 5.3 years, the strength of the concrete in the ocean was 15 to 20% less than that of continuously fog-cured concrete.

These findings raise a question as to the applicability of "concrete strength increases with age" as generally accepted (Ref 8). Massive offshore structures are typically fabricated in a seawater environment. If saturation is considered to occur, then the following interim guide can be used for strength gain with age. The initial 28-day fog-cured strength should be reduced by 10% to account for saturation effects. Subsequent in-situ strength increases with time may depend on the depth at which the concrete is located. Depth is important because it can influence the degree of saturation. At present, data are available at depths of a few thousand feet. For this case, the strength increase relative to the 28-day fog-cured strength appears to be nil at 1 year, 5% at 2 years, and 15% at 5 years.

For cases where the concrete is at a depth of a few hundred feet, it is hard to estimate the strength gain behavior. First, it is unknown how much of the wall thickness will become saturated. It could take months for several feet of thickness to become saturated. If the interior of the structure were to be at a relative humidity of less than 100%, the concrete would never become saturated. However, some of the concrete would be saturated near the outside wall, and that portion would exhibit a strength different from that not saturated. As a guide, the compressive strength should be reduced by 10% to account for saturation effects; then it is probably reasonable to permit a strength increase of 10% at 6 months and 15% at 12 months. These values are conservative from the on-land increase factors of 20% at 6 months, and 24% at 12 months.

Numerous cylinders, both cast and cored, were instrumented with strain gages to determine the elastic modulus and Poisson's ratio of the concrete. Table 3 summarizes the data, and Figures 11 through 14 show the stress-strain curves. The behavior of cored cylinders is presented as raw data, i.e., it has not been adjusted for drilling effect. The concretes were all linear up to about $0.5\ f'_c$. The elastic modulus of ocean-cured concrete was 30% less than that of the continuously fog-cured concrete. Although the elastic modulus was not determined for fog-cured concrete at the age of 28 days, it is reasonable to assume, based on data from similar concrete (Ref 5), that the elastic modulus of the ocean-cured concrete did not change significantly from that of the 28-day fog-cured specimens.

Short-Term Loading of Spheres

Implosion. The three spheres retrieved from the ocean were returned to the Laboratory for short-term loading tests. These tests were conducted in a pressure vessel where the external hydrostatic pressure was increased steadily until implosion.

While in the ocean, these spheres were subjected to a sustained load of about 50% their short-term ultimate strength for a period of 5.3 years. In previous work (Ref 5) identical specimens were tested under short-term loading where the specimens were not exposed to the long-term preloading. Table 4 shows the results from both types of short-term tests, with and without preload. Table 5 summarizes the results.

For the uncoated spheres, the preloaded sphere showed a decrease in implosion strength of about 8% compared to that of the non-preloaded spheres. The compressive strength of the saturated concrete was fairly well-defined for these tests. For the coated spheres, the preloaded spheres showed an increase in implosion strength of about 5% compared to that of the non-preloaded spheres. The actual increase

Table 3. Elastic Moduli and Poisson's Ratio Data

[Test specimen size was 6 x 12 inches (152 x 305 mm)]

Type of Specimen	Total Age	Main Curing Environment	Type of Cylinders	No. of Specimens	Elastic Modulus, E (psi x 10^6)	Poisson's Ratio, ν
Fog-cured	5.6 yr	100% RH; 73°F	cast	24	5.33	0.21
Ocean-cured	5.6 yr (includes initial 28 days in fog room and then 2 to 5 mo of on-land field curing 150 ft from shoreline)	ocean depth, 2,400 to 3,200 ft; 40°F	core	15	3.77[a]	0.24
On-land	5.6 yr (includes initial 28 days in fog room)	150 ft from shoreline	core	16	4.21[a]	0.22
	90 days (includes initial 28 days in fog room)	400 ft from shoreline in a building	cast	2	4.12	—

[a]Elastic modulus determined from unadjusted core data.

in implosion strength may have been greater than the reported 5% due to not defining as accurately the compressive strength for the preloaded spheres as for the other cases. The coated spheres from the ocean had relatively dry concrete. To obtain a compressive strength of dry concrete, the on-land concrete blocks were used. The evaporable moisture content of the on-land blocks was 2.7% by weight, which was less than the 3.5% by weight moisture content for the coated sphere wall (Appendix B). Hence, the compressive strength listed in Table 4 for Spheres no. 11 and 13 may be a little greater than the actual strength of the concrete in the sphere wall. If this potential error was corrected, the effect would be to increase the P_{im}/f'_c ratio for the coated preloaded spheres.

Table 5 shows that for non-preloaded spheres the dry concrete specimens had an implosion strength only slightly greater than that for the saturated concrete specimens. However, for the preloaded spheres, the dry concrete specimens were at least 14% stronger than the saturated concrete specimens. This difference in strength will be discussed in the next section.

The implosion data are limited. When the implosion strengths of dry and saturated preloaded specimens (P_{im}/f'_c = 0.299) were averaged and compared to those of the non-preloaded spheres (P_{im}/f'_c = 0.304), it was found that the overall effect of preloading the spheres to a stress level of about 50% their ultimate strength for 5.3 years was quite small.

Views of the imploded spheres are shown in Figures 15 through 18. The visual damage, in terms of fragmentation, is rather mild in comparison to non-preloaded specimens and, in particular, to specimens that have imploded in the

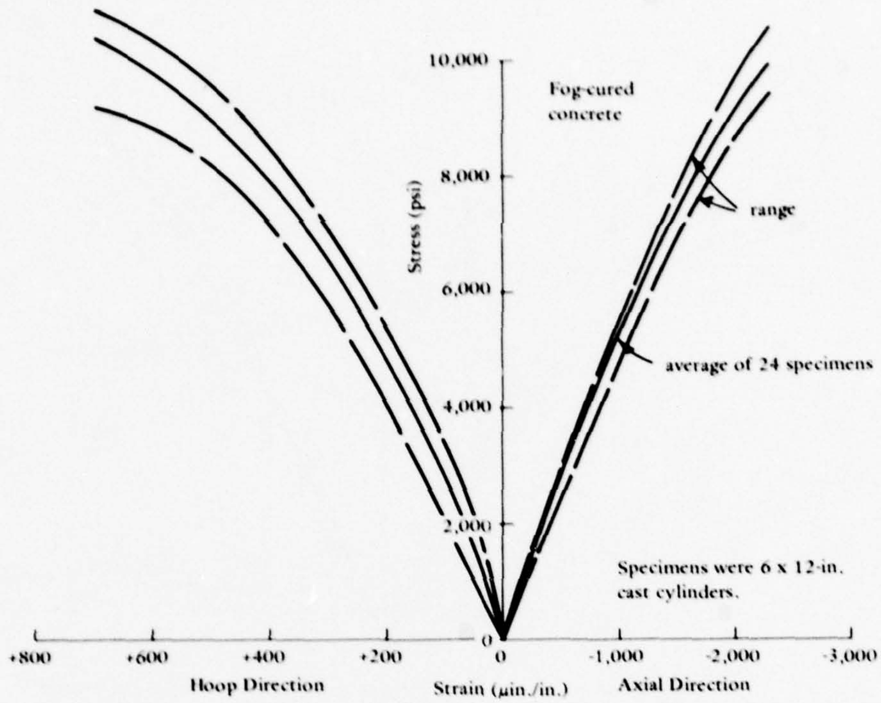

Figure 11. Uniaxial compressive tests of continuously fog-cured concrete for 5.6 years.

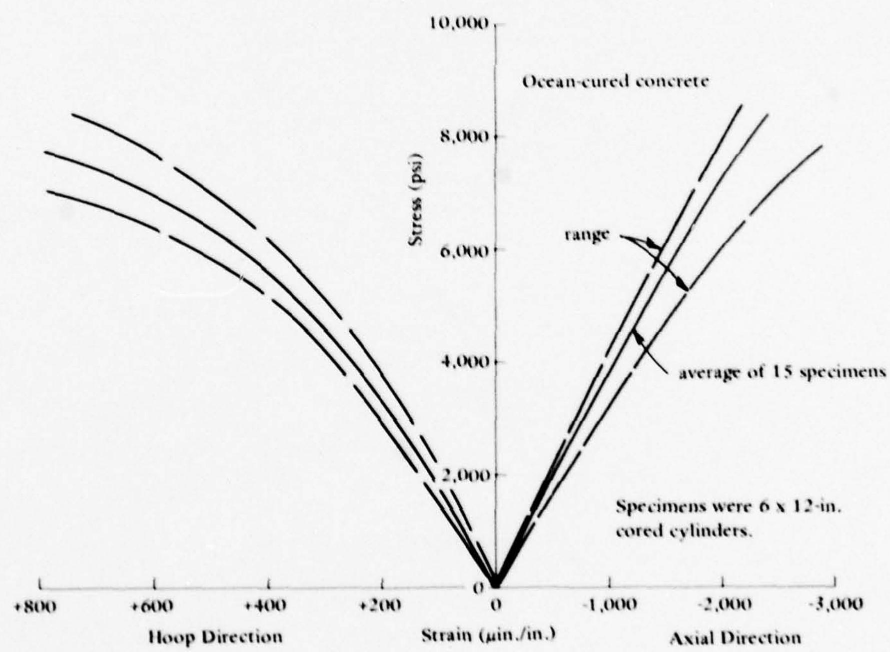

Figure 12. Uniaxial compressive tests of ocean-cured concrete for 5.6 years.

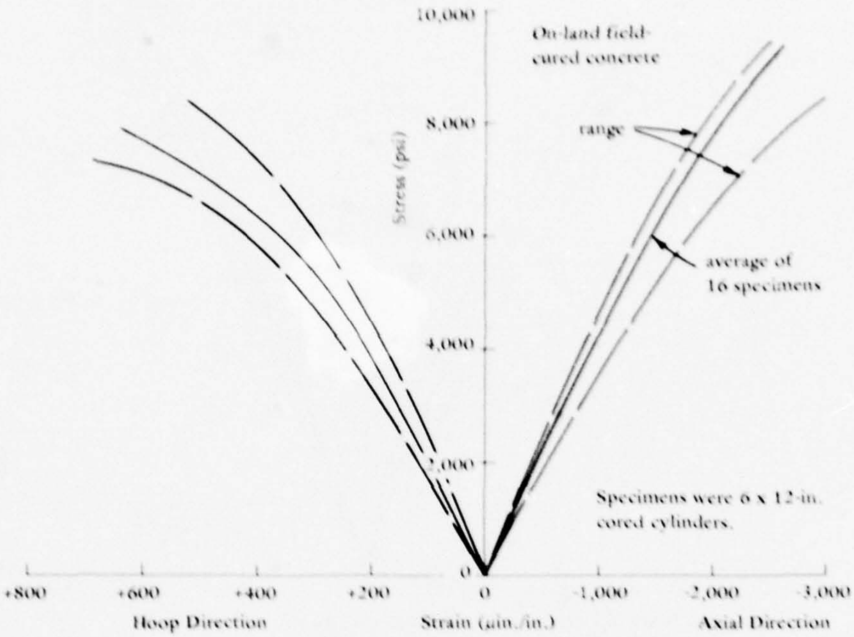

Figure 13. Uniaxial compressive tests of on-land field-cured concrete for 5.6 years.

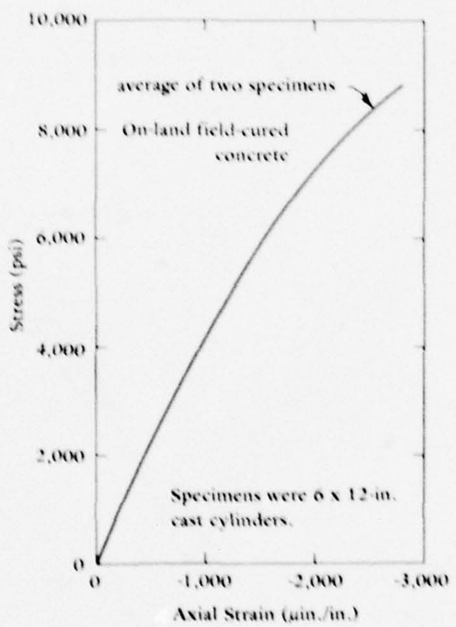

Figure 14. Uniaxial compressive tests of on-land field-cured concrete for 90 days (from Ref 5).

Table 4. Short-Term Loading Results of Concrete Spheres

Description	Sphere Designation	Concrete Condition[a]	Preload Pressure (psi)	Uniaxial Compressive Strength, f'_c (psi)	Implosion Pressure, P_{im} (psi)	Ratio, $\frac{P_{im}}{f'_c}$	Elastic Modulus of Sphere Wall, E (psi x 10^6)
Spheres preloaded in the ocean for 5.3 yr	11	dry	1,400	9,200[b]	2,970	0.323	5.05
	12	saturated	1,245	9,960[c]	2,750	0.276	5.20
	13	dry	1,175	9,760[b]	3,115	0.319	5.05
Non-preloaded spheres (after Reference 5)	CDS-1	dry	0	9,250	2,860	0.309	4.64
	CDS-2	dry	0	9,120	2,755	0.302	4.14
	CWS-3	saturated	0	7,960	2,500	0.314	—
	CWS-4	saturated	0	7,660	2,205	0.288	4.29

[a]Dry concrete corresponds to coated spheres, and saturated concrete corresponds to uncoated spheres.

[b]6 x 12-inch (152 x 305-mm) cylinders cored from on-land field-cured concrete blocks prepared from concrete used in spheres.

[c]6 x 12-inch (152 x 305-mm) cylinders cored from the ocean-cured concrete block attached to Sphere No. 12.

Table 5. Summary of Short-Term[a] Loading Results

Spheres	Implosion Pressure to Compressive Strength Ratio, P_{im}/f'_c, for Spheres	
	Coated (dry concrete)	Uncoated (saturated concrete)
Preloaded[b]	0.321	0.276
Non-Preloaded (after Ref 5)	0.306	0.301

[a]Spheres tested in a pressure vessel.

[b]In the ocean for 5.3 yr.

ocean. The zones of failure for Spheres no. 11 and 12 (Figures 15 and 16) appeared to be from crushing of concrete and were more localized than for the non-preloaded spheres. Sphere no. 13 showed a failure zone (Figures 17 and 18) that was more typical of the non-preloaded spheres. A shear-compression-type failure mode for a section of wall was evident for about 50 inches (130 mm) in length.

The spheres that imploded in the ocean were found totally fragmented. In a pressure vessel, once failure of a sphere began, the pressure load dropped off rapidly. This did not occur in the ocean, and, hence, a sphere was subjected to extremely violent shock forces when the water collapsed the walls. Figure 19 shows the debris on the seafloor for Sphere no. 1 that imploded at a depth of 5,075 feet (1,547 m).

Strain Behavior. Strain behavior for the spheres tested in the pressure vessel was monitored by measuring the quantity of water displaced from the interior of the sphere while under load.* A change of interior volume is a direct function of the change in radius, and the change in radius is a direct function of hoop strain. The displaced water was measured to an accuracy of ± 10 ml, which converted to a strain accuracy of ± 2 in./in. This is applicable only when membrane displacements account for most of the change in volume. Near failure, displacements due to flat-spot development can contribute significantly to the displaced water.

Figure 20 shows the raw data of pressure versus displaced water for the spheres. Other scales show the wall stress and strains. A similar presentation of results is given in Figure 21 for the non-preloaded spheres (after Ref 5). The dry concrete spheres were able to withstand about 20% more ultimate strain than the saturated spheres before imploding.

It was quite apparent from the data that saturated concrete behaved differently than dry concrete. However, at this time, data do not exist on the stress-strain behavior of concrete control cylinders that are saturated and uniaxially loaded while in a hydrostatic pressure environment. This sphere test program (Figures 20 and 21) provides the first data that show saturated concrete under hydrostatic pressure does not perform as well as similar dry concrete.

Table 4 lists the stiffness, or elastic modulus, for the walls of the spheres. The average modulus value for the three ocean spheres was 5.1×10^6 psi (35.2 GPa); for the non-preloaded spheres, it was 4.4×10^6 psi (30.3 GPa). This difference was due to the effect of the preload and is a well-known effect of concrete creep (Ref 8). For 5.3 years the concrete in the ocean spheres experienced creep under a wall stress of about 5,000 psi.

Concrete creep and a triaxial loading condition explains why the modulus of 5.1×10^6 psi (35.2 GPa) for the wall of the preloaded sphere was greater than that given in Table 3 for the ocean-cured concrete block, where the modulus was 3.77×10^6 psi (26.0 GPa). The concrete block in the ocean was not stressed like the sphere wall; it was saturated with seawater and in a state of equilibrium with the environment.

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*This technique was used in Reference 5 with excellent results; the same procedures were applied in these tests.

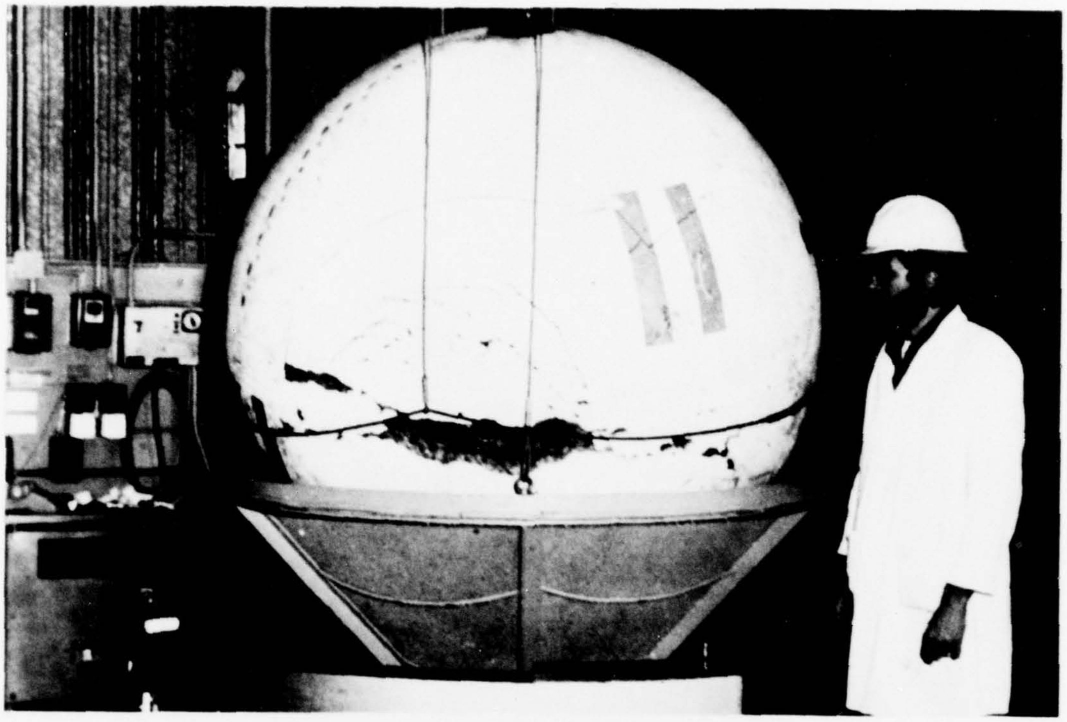

Figure 15. Post-implosion view of Sphere no. 11.

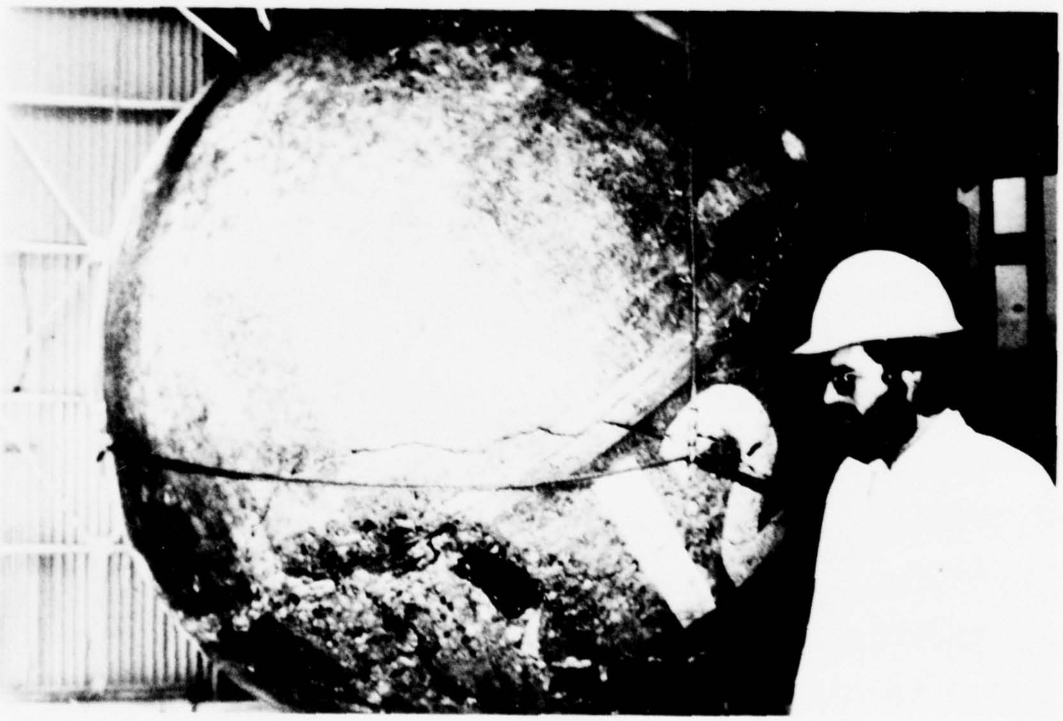

Figure 16. Post-implosion view of Sphere no. 12.

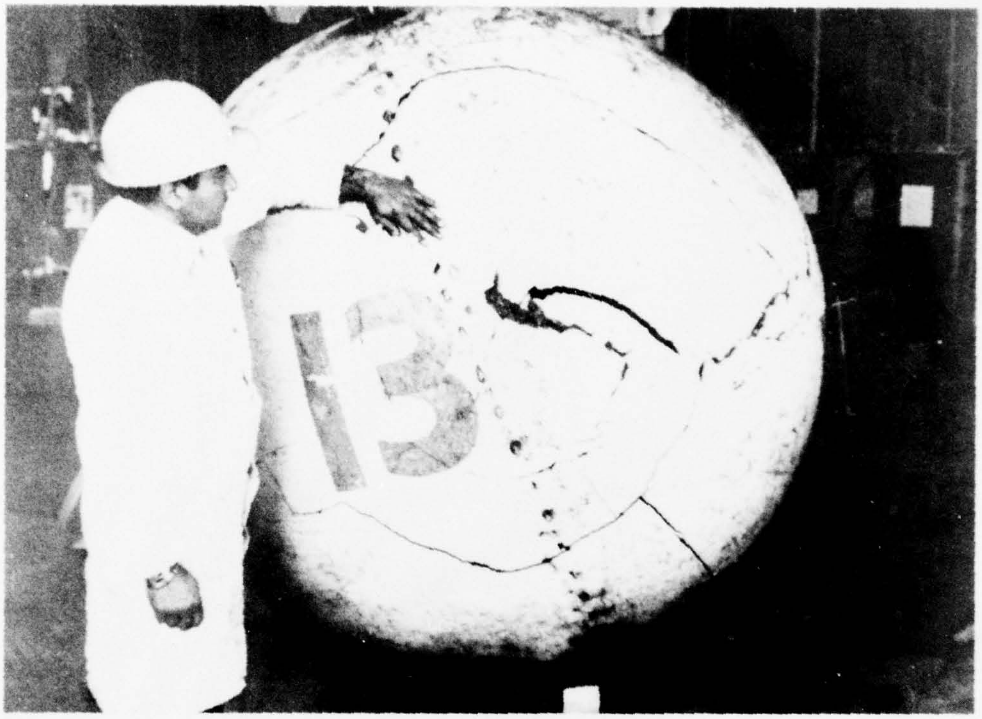

Figure 17. Post-implosion view of Sphere no. 13.

Figure 18. This view of Sphere no. 13 is typical of post-implosion for non-preloaded spheres. The missing concrete was pushed to the interior of the sphere. Shear-compression plane runs from equator to above the numeral 13.

Figure 19. Debri on the seafloor after Sphere no. 1 imploded at a depth of 5,075 feet. The submersible's manipulator arm is seen at the top of the photograph, and the dark area under the arm is vegetation-like growth.

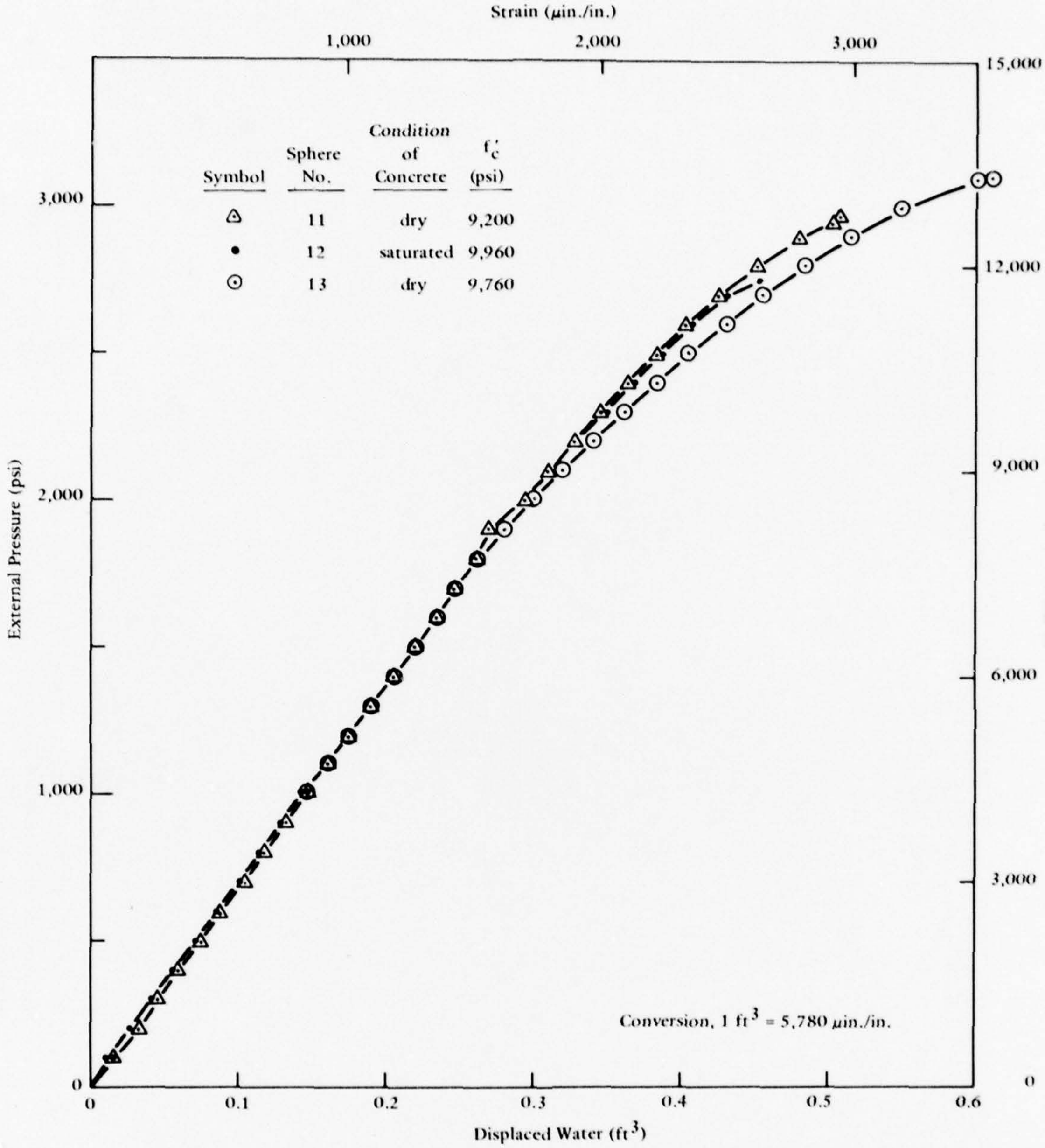

Figure 20. Displaced water versus pressure for short-term implosion of preloaded spheres.

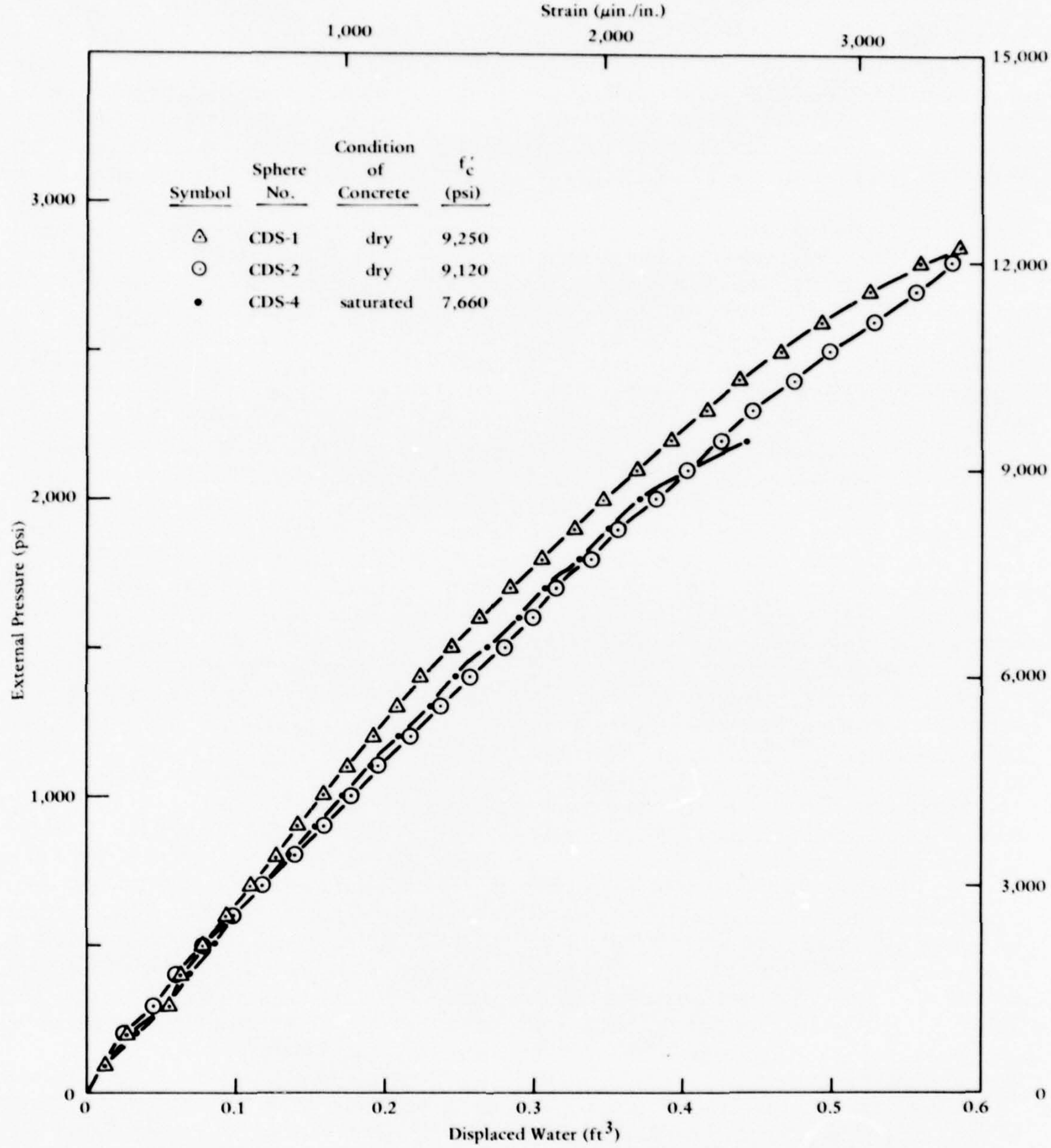

Figure 21. Displaced water versus pressure for short-term implosion of non-preloaded spheres (from Ref 5).

Long-Term Loading of Spheres

Of the original eighteen spheres in the ocean, three spheres have imploded at depth. The time-to-failure for each of the spheres has had to be estimated because the clocks contained in two of them have not been found. Sphere no. 3 evidently imploded on descent to the seafloor at 4,330 feet (1,320 m) because the concrete fragments were widely scattered. Spheres no. 1 and 7 had a time-to-failure that was between the beginning of the test and the day of their first inspection. For these specimens the concrete fragments were in a localized area.

Detailed data for these spheres and the other spheres still intact on the seafloor are given in Table 6. This table also shows the calculations for the relative load level, i.e., the ratio of sustained pressure to the predicted implosion pressure, P_S/P_{im}^P, for each sphere. The relative load level for the spheres changed between the beginning of the test and the 5.3-year period as the concrete became stronger with time. Using data from Figure 7 for dry concrete and Figure 8 for saturated concrete, the 28-day fog cure compressive strength was adjusted to estimate the strength at 5.6 years.

The long-term loading failure behavior for the ocean spheres is shown in Figure 22. Data from spheres tested in a pressure vessel (Ref 5) are also presented in Figure 22 and summarized in Table 7. The results of Stockl (Ref 9) are shown by an average data curve which represents hundreds of tests on uniaxially loaded specimens. With two exceptions, the sphere results are in agreement with Stockl's findings. From his data, it appears that the safe relative load level is about 0.75.

Stockl presented an interesting discussion on long-term loading. When a structure is initially placed under sustained load, the creep behavior of concrete causes degradation of strength by forming microcracks. At the same time, in the presence of moisture, hydration of cement causes a strengthening of the concrete. Long-term loading to failure occurs when microcracks from creep progress at a faster rate than strengthening from cement hydration. Since creep effects slow down with time, strength gain from cement hydration has a chance to catch up and overtake the creep-induced strength reductions. The rate of cement hydration is dependent upon the amount of free cement available within the concrete before it is placed under sustained load. The practical significance of this condition is that once the "critical duration of load" is over and hydration strengthening occurs at a faster rate than creep damage, the specimen will never fail from creep. The critical duration of sustained load can be days when applied to young concrete and years for old concrete. For the spheres in the ocean, the critical duration of load was probably on the order of months. Hence, according to Stockl, any sphere that has not failed after 5.3 years under sustained load should not fail in the future.

In Figure 22, for Sphere no. 1 (5,075 feet) and Sphere no. 7 (3,725 feet) the time-to-failure is shown as a dashed line. The datum point for the spheres was plotted at 10 days as a conservative estimate. For Sphere no. 3 (4,330 feet), a wide scatter of fragments on the seafloor indicated that the specimen failed during descent.

A valuable supplement to the failure data was the results from the spheres that had not failed. Figure 23 shows the relative load levels for the spheres in the ocean that are still intact. Stockl's curve is shown to lie above the data. The relative load levels experienced by the spheres in the ocean are shown to decrease with time as the strength of concrete increases.

Table 6. Summary of Long-Term Loading Data From Spheres Tested in Ocean

Sphere No.	Condition of Concrete in Sphere	Sustained Pressure in the Ocean, P_s (psi)	Beginning of Ocean Test				At Implosion or Last Inspection				Time to Failure (day)
			Age of Concrete (day)	Uniaxial Compressive Strength, f'_c (psi)	Predicted Implosion Pressure[a] P^P_{im} (psi)	Relative Load Level, P_s/P^P_{im}	Age of Concrete (day)	Uniaxial Compressive Strength,[b] f'_c (psi)	Predicted Implosion Pressure[a] P^P_{im} (psi)	Relative Load Level, P_s/P^P_{im}	
1	dry	2,255	174	8,940	2,710	0.83	1,294[c]	9,440[c]	2,860	0.79	1 to 1,120
2	dry	2,165	162	8,970	2,715	0.80	2,112	10,470	3,170	0.68	Intact
3	dry	1,925	134	8,840	2,680	0.72	134	8,840	2,680	0.72	0
4	wet	1,860	172	7,600	2,300	0.81	2,122	9,290	2,815	0.66	Intact
5	wet	1,820	158	7,690	2,330	0.78	2,108	8,920	2,700	0.67	Intact
6	wet	1,720	143	8,370	2,535	0.68	2,093	9,300	2,815	0.61	Never inspected
7	dry	1,655	126	9,480	2,870	0.58	557[c]	9,480[c]	2,870	0.58	1 to 430
8	dry	1,630	111	9,030	2,735	0.60	2,061	9,920	3,005	0.54	Intact, but flooded
9	wet	1,465	94	7,820	2,370	0.62	2,027	7,990	2,420	0.61	Intact
10	wet	1,420	97	8,330	2,525	0.56	2,030	9,120	2,765	0.51	Intact
11	dry	1,395	113	9,190	2,785	0.50	2,063	9,950	3,015	0.46	Intact
12	wet	1,240	89	7,430	2,250	0.55	2,022	8,350	2,530	0.49	Intact
13	dry	1,170	105	9,370	2,840	0.41	2,005	10,080	3,055	0.38	Intact
14	dry	1,085	144	8,170	2,475	0.44	2,094	9,220	2,795	0.39	Intact
15	wet	1,020	74	7,830	2,370	0.43	2,024	9,010	2,730	0.37	Intact
16	wet	940	67	7,780	2,355	0.40	2,017	8,330	2,525	0.37	Intact
17	wet	880	52	7,730	2,340	0.38	2,002	8,920	2,700	0.33	Intact
18	wet	820	45	7,590	2,300	0.36	1,995	9,200	2,790	0.29	Intact

[a] P^P_{im} = $0.303 f'_c$ obtained from short-term loading tests.

[b] f'_c is estimated for last inspection by using Figures 7 and 8.

[c] Represents maximum value; sphere imploded sometime during this period.

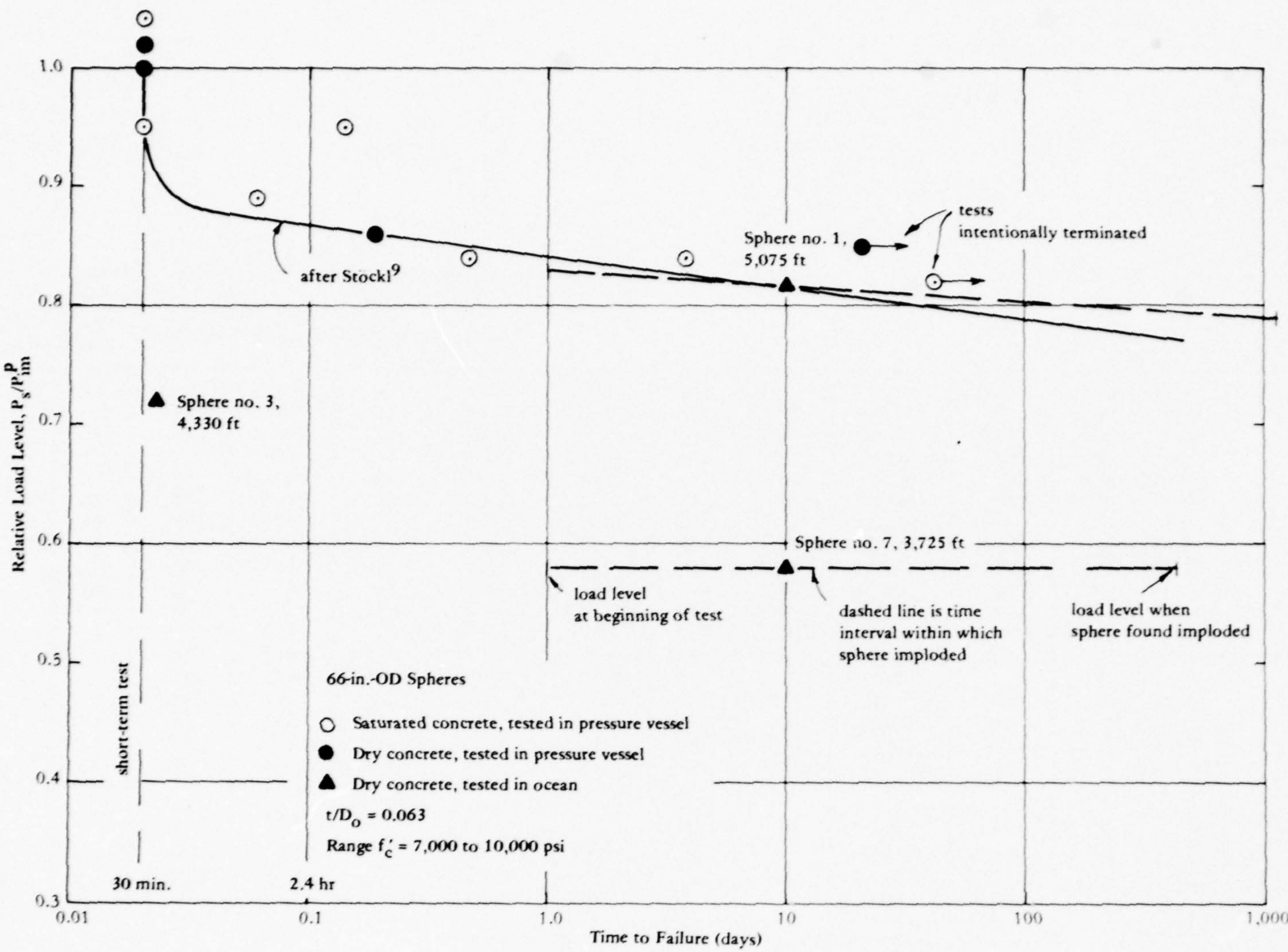

Figure 22. Time to failure of concrete spheres under long-term hydrostatic loading.

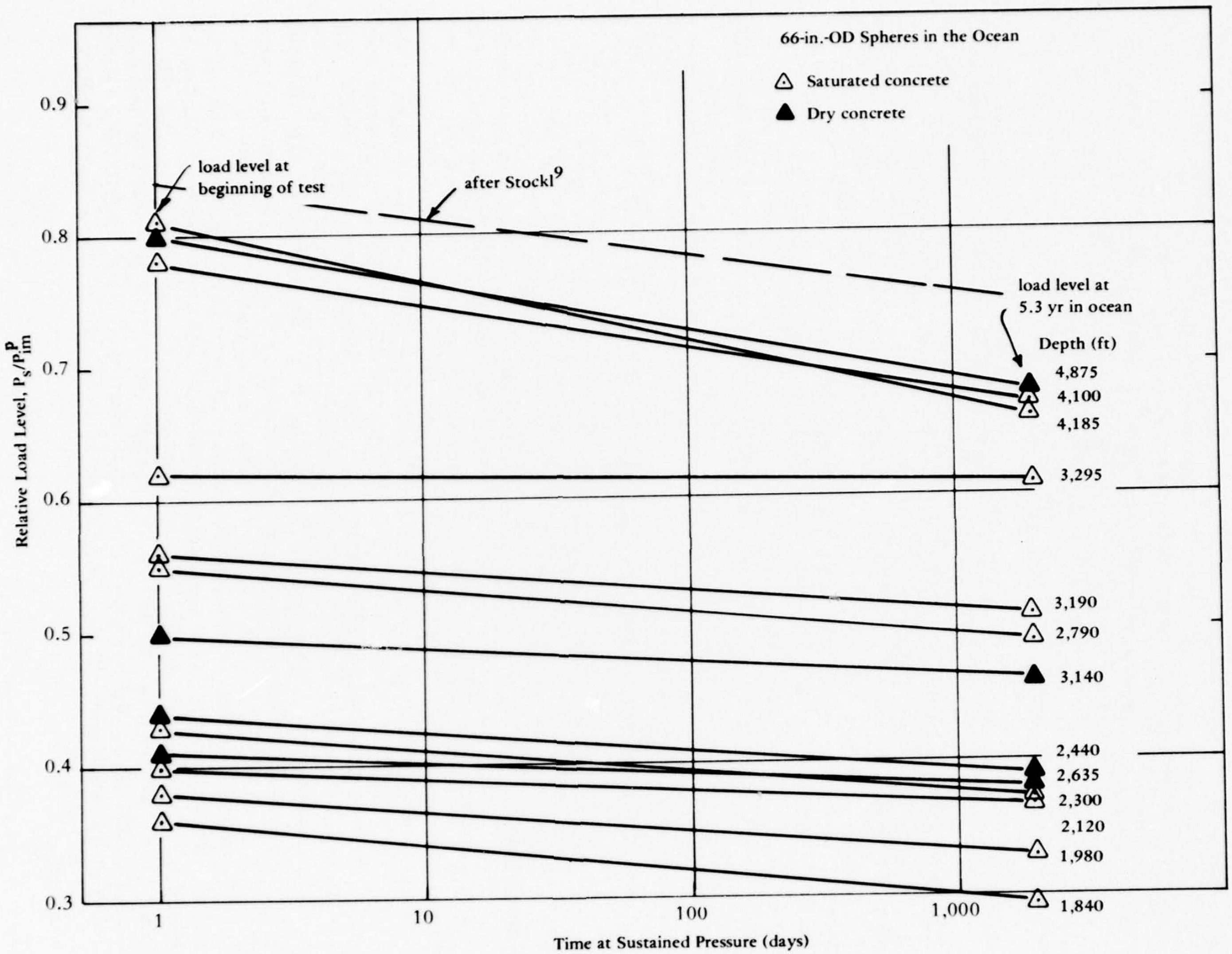

Figure 23. Relative load level for spheres still intact in the ocean.

Table 7. Summary of Long-Term Loading Data From Spheres Tested in Pressure Vessel (after Ref 5)

Sphere No.	Condition of Concrete	Sustained Pressure, p_s (psi)	Uniaxial Compressive Strength,[a] f'_c (psi)	Predicted Implosion Pressure,[b] P_{im}^p (psi)	Relative Load Level, $\frac{p_s}{P_{im}^p}$	Time to Failure (day)	Comment
CWL-5B	wet	2,280	7,900	2,395	0.95	0.14 (200 min)	
CWL-6	wet	1,670	6,740	2,040	0.82	41.82	Test intentionally terminated
CWL-7	wet	1,940	7,170	2,170	0.89	0.06 (90 min)	
CWL-8	wet	1,845	7,210	2,185	0.84	0.47 (680 min)	
CWL-9B	wet	1,905	7,440	2,255	0.84	3.77	
CDL-10	dry	2,405	9,420	2,855	0.86	0.19 (270 min)	
CDL-11	dry	2,065	7,940	2,415	0.85	20.92	Test intentionally terminated

[a]Strength given for weaker hemisphere.

[b]P_{im}^p = 0.303 f'_c obtained from short-term loading tests.

Permeability

Table 1 gives the change in number of chain links suspended off the seafloor by the spheres. The change in link count was due to a loss of buoyancy by the spheres because of weight gain from water absorption and permeability. The loss of buoyancy was converted to a volume of seawater taken on by the spheres.

Total water intake by a sphere included the quantity of seawater absorbed by the concrete and permeated through the wall. The quantity of seawater absorbed by the concrete was calculated by assuming 3% by weight absorption. Three percent absorption was determined for identical concrete by extrapolating data obtained at 550 feet (168 m) pressure head for 86 days (Ref 4) to a time period of 3 years when it was estimated that absorption was complete.

For Sphere no. 12, which was uncoated, it was predicted from the chain link count that the interior contained 1.38 cu ft (39 liters) of water. The actual measured volume of water was 1.24 cu ft (35 liters). This close prediction of the actual permeated seawater not only indicates the 3% by weight absorption is a fair estimate, but also that the initial calculations of the original number of chain links suspended

off the seafloor was accurate. In Reference 1 concern was expressed that the original number of links off the seafloor could be in error by ±1.5 links (equivalent to 0.73 cu ft or 21 liters). With the data from Sphere no. 12, it is now known that that error estimate was too high. A new estimate of error is ±0.5 link (0.24 cu ft or 7 liters), which is also the error estimate between different inspections.

Figure 24 shows the relationship between total water intake and time in the ocean for all of the spheres (except Spheres no. 17 and 18, which were half coated) where chain link count data were obtained. The coated spheres do not show any evidence of having permeated water. This case is known to be true for Spheres no. 11 and 13. The coated spheres range in depth from 2,440 to 4,875 feet (744 to 1,486 m).

The waterproof coating appeared quite effective. This was an unanticipated finding, because the coating was not a complete barrier. Pin-holes or "fish-eye" openings existed in the coating. The coating also bridged air pockets in the wall near the surface; these locations had the coating broken because the water pressure pushed the coating into the air pocket. Water definitely had access to the concrete wall through these openings.

When a hole was drilled in the walls of Spheres no. 11 and 13, the concrete was found to be quite dry in appearance. It is apparent that the pin-hole openings became watertight with time. Continued hydration of cement, microorganisms, and chemical changes were probably some of the causes for the concrete becoming watertight. Whatever the mechanism, it can be speculated that it was functioning in the uncoated concrete too. From Figure 24, it is shown that, in general, the uncoated concrete spheres became watertight. In less than 1 year, the uncoated spheres absorbed (and permeated) water at a faster rate than the coated spheres. However, after 1 year the additional water intake was quite small.

One method of analyzing permeability results is to apply D'Arcy's viscous flow equation. For a sphere, this equation can be expressed as:*

$$K_c = \frac{Q_p \, t}{T \, A_s \, h} \qquad (1)$$

where K_c = permeability coefficient, ft/sec (m/sec)

Q_p = quantity of permeated seawater, ft^3 (m^3)

T = time (sec)

t = wall thickness, ft (m)

A_s = interior surface area, ft^2 (m^2)

h = pressure head, ft (m)

D'Arcy's theory assumes K_c to be constant with time. However, the permeability results from the spheres show that K_c decreases with time. To account for the change in rate of K_c, a secant K_c is utilized. This is analogous to the secant modulus of elasticity for nonlinear materials such as concrete.

In Figure 25 the secant K_c values are shown as a function of time in the ocean. Data from two spheres tested in a pressure vessel for up to 42 days are included. These spheres were similar to the ones in the ocean. It is interesting

*This expression is different from that given in References 1 and 5 because A_s is now defined as the interior surface area and not as mentioned previously as the exterior surface area. This revised equation will give K_c values 30.6% greater than the previous equation.

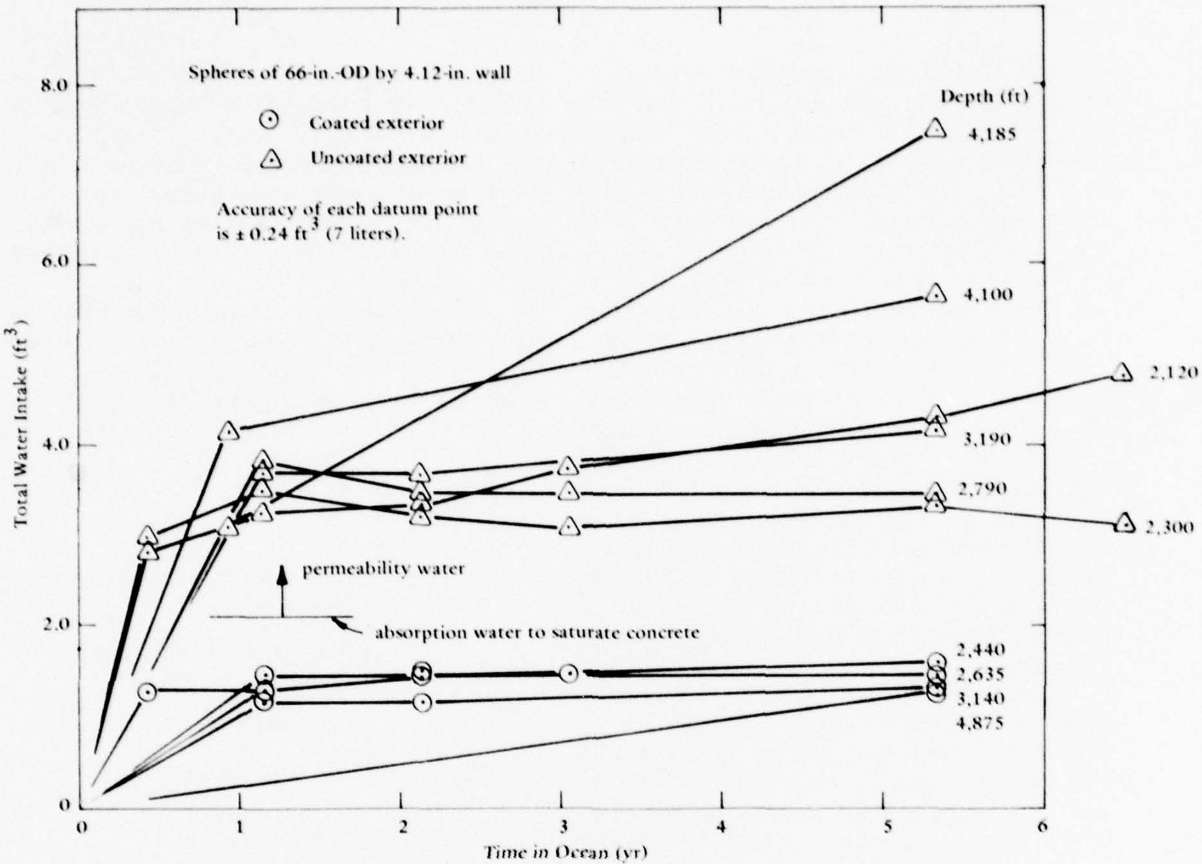

Figure 24. Total water intake for spheres in the ocean for long time periods.

that extrapolations of the pressure vessel test results yield results close to the actual values obtained from the spheres in the ocean.

The data from the spheres compared moderately well with results from Powers et al. (Ref 10) who studied cement pastes. The water-to-cement ratio for the pastes varied from 0.3 to 0.7, and the measured K_c values (initial tangent K_c) ranged from 0.3×10^{-14} to 400×10^{-14} ft/sec (0.1×10^{-14} to 120×10^{-14} m/sec), respectively.

For a water-to-cement ratio of 0.4, which was equivalent to that for the concrete in the spheres, Power's results showed a K_c of about 3.3×10^{-14} ft/sec (1.0×10^{-14} m/sec). This was an order of magnitude lower than that for the concrete in the spheres tested in the pressure vessels. Powers did not discuss any indication of permeability results decreasing with time, as was found in this study.

Durability

Samples of 5.6-year-old concrete from the ocean spheres, both coated and uncoated, and from the on-land and continuously fog-cured cylinders were analyzed by x-ray diffraction techniques by Prof. Mehta at the University of California at Berkeley. He determined

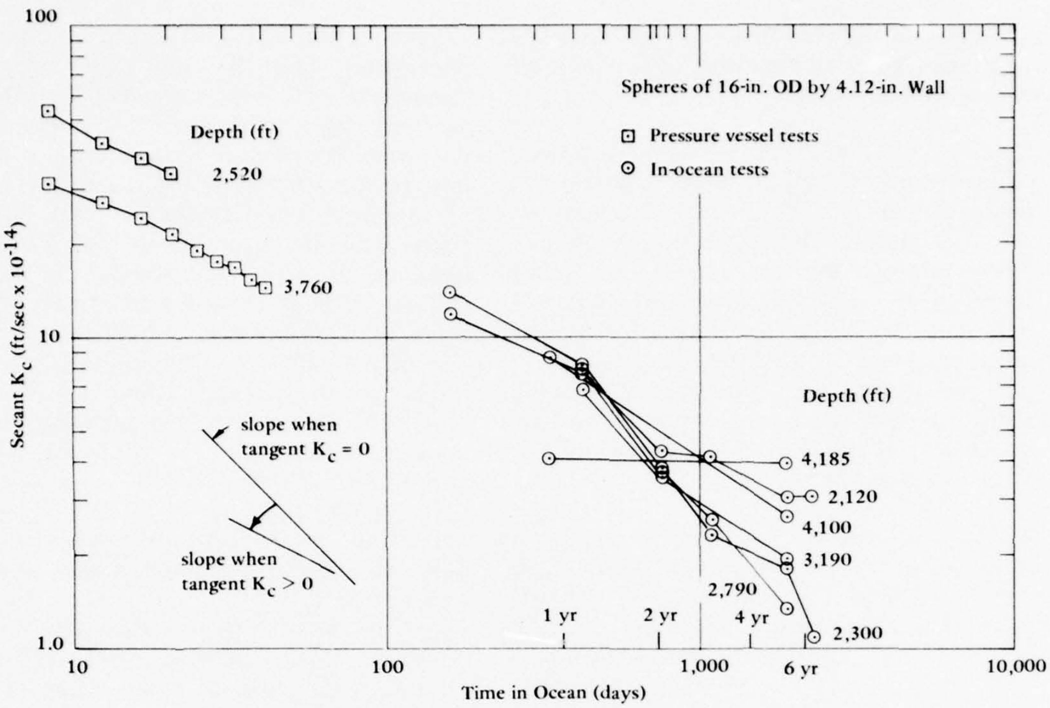

Figure 25. Permeability of uncoated spheres expressed as secant K_c versus time.

the chemical composition of the cement pastes; his report is given in Appendix E. All samples showed that the cement compounds were hydrated. The samples also showed that substantial amounts of calcium hydroxide were present, which indicates the hardened cement pastes were undamaged. No evidence was present of harmful chemical compounds. The ocean concrete remained essentially unaltered from the fog-cured concrete.

FINDINGS

1. Concrete that was placed in the ocean decreased in compressive strength by at least 10% due to saturation. A time period of from 1 to 2 years in the ocean was required to regain a strength equal to that of the 28-day fog-cured strength.

2. After 5.3 years in the ocean, concrete showed a compressive strength that was 15% greater than its 28-day fog-cured

strength. However, this strength was still 15% less than companion concrete continuously fog-cured.

3. Three spheres were retrieved from the ocean where they had been exposed to a preload of 50% of their ultimate strength for 5.3 years. These preloaded spheres were tested in the laboratory under short-term loading and, in general, behaved similarly to that of non-preloaded spheres. Whether preloaded or non-preloaded, the saturated (uncoated) concrete spheres had a tendency to fail at lower pressures than those of dry (coated) concrete spheres.

4. Three of the original eighteen spheres have imploded in the ocean under long-term loading. The remaining spheres have withstood load levels of 0.3 to 0.8 of their predicted short-term strength.

5. The permeability of concrete in uncoated spheres has shown a decrease in rate with time and, in several cases, the permeation of seawater through the concrete wall has stopped. Coated (waterproofed) spheres remained dry on the interior.

6. X-ray diffraction analysis of the fog-cured and ocean-cured concrete has shown the 5.3-year ocean-cured concrete - whether coated or uncoated - to be essentially unchanged from the fog-cured concrete.

SUMMARY

After 6.4 years in the ocean, the long-term test on concrete spheres at deep ocean depths has demonstrated several important factors that will result in design criteria for undersea concrete structures. Those items are listed in the Findings section above. To summarize: (1) the compressive strength of concrete decreased slightly due to becoming saturated with seawater, (2) the rate of strength gain with time for concrete in the deep ocean was slower than that for concrete cured in a standard fog room, (3) spheres exposed to a load 50% of their short-term strength for 5.3 years behaved in a manner similar to that of spheres that were not exposed to a long-term load, (4) twelve spheres are still in the ocean and are withstanding pressure loads that range from 1,840 to 4,875 feet (560 to 1,486 m), (5) the permeability of uncoated concrete was quite low, (6) if complete watertightness is desired, a waterproof coating was found to be effective, and (7) the durability of concrete in the deep ocean was found to be excellent.

The results from this study show undersea concrete structures to behave exceptionally well at deep ocean depths. The strength, permeability, and durability of the spheres are within or exceed engineering acceptability limits. Confidence in using concrete for undersea structures is substantiated and enhanced by the results of this ocean test. The test is continuing, and additional data will be forthcoming.

ACKNOWLEDGMENTS

The authors wish to acknowledge the able assistance of Mr. Phillip C. Zubiate as the senior project technician for this task from its beginning, and the support and cooperation of the Navy's Submarine Development Group One for its services in conducting the submersible operations.

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Appendix A

EFFECT OF DRILLING CORES ON COMPRESSIVE STRENGTH

It is generally known that the compressive strength of core specimens obtained from a structure is usually less than that of standard laboratory cast cylinders. This observation is the result of many influencing parameters, one of which is the effect of drilling the core specimens. Other parameters are: curing environment, size of core specimen, and direction of coring compared to casting (to name a few). The specific topic of drilling effect had not been directly addressed in past studies. However, investigations by Bloem (Ref 11) and Campbell and Tobin (Ref 12) gave data suitable for estimating the drilling effect.

Both investigations used concrete slabs that had provisions for making and curing cast cylinders as part of the slab. At the time of test, the cast cylinders were removed from the slab, and then core specimens of the same size as the cast cylinders were drilled from the slab.

The Bloem study used plastic inserts that were set in the slab to make the cast cylinders; these were subsequently "pushed-out." Both the cast and cored cylinders were soaked for 40 hours prior to testing to insure similar moisture contents. The Campbell and Tobin study used concrete having two cement contents, 5.33 and 7.33 sacks per cu yd. Cast cylinders were made in metallic molds and then placed in holes in the slab. The cast and cored cylinders were soaked prior to testing.

The uniaxial compressive strength data of select test runs are given in Table A-1. The observed effect of drilling is to reduce the strength of the cast cylinders by a factor of 0.93. For this report, the inverse, 1.07, is the factor to increase the strength of cored specimens so that they become equivalent to cast cylinders.

This factor of 1.07 was in close agreement with that of Murphy (Ref 13) who mentioned a factor of 1.06 but did not present test results or the background source.

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Table A-1. Compressive Strength Data on Effect of Drilling Cores

Investigator	Size of Specimen (in.)	Type of Cement	No. of Specimens	Compressive Strength at 28 Days for Standard Laboratory Conditions, f'_c (psi)	Test Age (days)	Compressive Strength, f'_c (psi) for — Cast Cylinders	Compressive Strength, f'_c (psi) for — Cores	Core/Cast	Coefficient of Variation (%)
Bloem (Ref 11)	4x6	Type I		3,730					
			3		3	1,750	1,700	0.971	
			3		7	2,310	2,290	0.991	
			3		28	3,210	3,040	0.947	
			3		91	3,420	3,370	0.985	
			3		364	3,450	3,025	0.877	
								avg 0.954	4.9
	4x6	Type III		5,490					
			3		3	3,710	3,250	0.876	
			3		7	3,770	3,510	0.931	
			3		28	4,160	3,640	0.875	
			3		91	4,440	4,130	0.930	
			3		364	4,270	3,500	0.820	
								avg 0.886	5.2
	4x6	Type III		4,150					
			3		1	2,980	2,770	0.930	
			3		3	3,110	2,910	0.936	
			3		7	3,280	3,020	0.921	
			3		28	3,340	3,060	0.916	
			3		91	3,540	3,180	0.898	
			3		364	3,390	2,850	0.841	
								avg 0.907	3.9
Campbell and Tobin (Ref 12)	6x12	Type II		4,515					
			4		28	4,150	3,850	0.928	
			4		56	4,195	4,140	0.987	
			4		84	4,660	4,095	0.879	
								avg 0.931	5.8
	6x12	Type II		5,870					
			4		28	5,280	5,345	1.012	
			4		56	5,460	5,390	0.987	
			4		84	6,000	5,695	0.949	
								avg 0.983	3.2
								overall avg 0.932	

Appendix B

EARLY COMPRESSIVE STRENGTH DATA OF SPHERES

Table B-1 lists the uniaxial compressive strength data for all the spheres in a manner similar to that in Reference 1, Table A-2 on Concrete Control Cylinder Data. This new table includes the coefficients of variation.

Table B-1. Early Compressive Strength Data of Spheres

[Each compressive strength value is average of three 6 x 12-in. (152 x 305-mm) cast cylinders.]

Sphere No.	Hemisphere No.	28-Day Fog Cure		Prior to Ocean Emplacement				
		Compressive Strength, f'_c (psi)	Coefficient of Variation (%)	Compressive Strength, f'_c, of Wet Concrete (psi)	Coefficient of Variation (%)	Compressive Strength f'_c, of Dry Concrete (psi)	Coefficient of Variation (%)	Age (days)
1	W4	8,520	0.1			8,940	1.5	174
	W35	8,070	2.1			9,360	1.5	65
2	W8	8,250	2.9			9,950	3.3	164
	W7	7,940	0.6			8,970	4.5	162
3	W15	8,520	1.5			8,840	1.5	134
	W16	8,400	1.9			9,650	2.0	132
4	W6	8,760	0.7	8,320	5.8			170
	W5	8,050	1.5	7,600	2.7			172
5	W10	7,730	1.1	8,090	2.9			156
	W9	8,240	1.7	7,690	1.7			158
6	W14	8,580	1.8	8,510	1.6			143
	W13	8,060	1.5	8,370	2.6			144
7	W20	7,660	1.7			9,530	2.3	117
	W17	7,550	5.5			9,480	2.3	126
8	W22	7,520	2.2			9,030	1.2	111
	W19	8,410	3.2			9,380	5.7	119
9	W28	6,920	1.8	7,820	5.5			94
	W25	8,070	3.4	8,740	2.7			104
10	W30	8,190	1.2	8,560	4.4			88
	W27	7,900	0.2	8,330	9.6			97
11	W24	7,540	3.8			9,820	5.6	103
	W21	7,720	2.7			9,190	3.3	113
12	W32	7,570	0.6	8,390	6.7			80
	W29	7,240	3.0	7,430	0.6			89
13	W26	8,070	4.5			10,210	5.3	98
	W23	7,640	2.0			9,370	1.2	105
14	W12	6,990	2.1			8,170	1.3	144
	W11	7,550	3.0			9,200	2.0	148
15	W34	8,170	2.3	7,830	4.9			74
	W31	7,810	1.4	8,740	1.9			82
16	W36	7,220	2.0	7,780	1.7			67
	W33	7,930	0.4	8,340	0.3			75
17	W39	8,050	1.1			9,050	4.2	51
	W40	7,730	2.0	7,730	5.0			52
18	W41	8,620	2.3			8,770	5.2	48
	W42	7,970	2.1	7,590	4.3			45

Appendix C

MOISTURE CONTENT OF CONCRETE SAMPLES

Tests were conducted on concrete fragments from ocean-cured spheres and blocks, on-land-cured blocks, and fog-cured cylinders to determine the relative free moisture contents associated with the different curing environments. These data were obtained by drying specimens in a 50% RH, 70F environment for 4 months and then at 130F (55C) for 3 weeks. The data are presented in Table C-1 and Figure C-1.

Moisture contents for the continuously fog-cured cylinders, ocean-cured blocks, and uncoated ocean-cured sphere were similar. The concrete in the coated ocean-cured sphere had a lower moisture content, and the on-land field-cured block had a still lower moisture content.

The moisture content of the concrete in the coated spheres represents the condition of the concrete after the spheres were tested in the pressure vessel. The spheres in the ocean probably had a lower moisture content. This conclusion can be presented because of an observation made during test. Prior to tests in the pressure vessel, the interior volume of the sphere was filled with water for the purpose of measuring the change in volume of the sphere during pressurization. The interior surface of the sphere was not coated. For Sphere no. 13, the specimen had water in its interior for about 16 hours, at which time it was observed that additional water had to be added to completely fill the interior again. A certain quantity of water was absorbed by the dry concrete before the test. For Sphere no. 11, water was in contact with the dry concrete for only about 4 hours.

In addition to drying some samples, other samples from the ocean-cured blocks and coated sphere wall were saturated in a pressure vessel. When the water gained was added to the water lost, the total water content for the blocks was about 5.13% by weight, and for the coated sphere wall, it was about 5.55% by weight. The average water content was 5.34% by weight, which represents an average void volume in the concrete of 12.5%.

Table C-1. Moisture Content of Concrete

Environmental Condition for Concrete Samples	Samples in Original Condition Placed in Pressure Vessel at 15,000 Psi for 7 Days			Samples in Original Condition Dried-Out by —					
				50% RH, 70°F for 4 Months			Additional 3 Weeks at 130°F		
	Water Gain (% by wt)	No. of Samples	Coefficient of Variation (%)	Water Loss (% by wt)	No. of Samples	Coefficient of Variation (%)	Total Water Loss (% by wt)	No. of Samples	Coefficient of Variation (%)
On-land field-cured for 5.6 yr									
Interior of blocks	–	–	–	0.87	12	21.8	2.61	12	12.3
Exterior of blocks	–	–	–	1.78	4	27.5	2.76	4	16.7
Fog-cured for 5.6 yr	–	–	–	2.47	18	8.9	4.37	18	8.0
Ocean-cured for 5.3 yr									
Blocks (uncoated)	0.83	2	56.6	2.83	8	4.2	4.72	10	5.5
Coated sphere wall	1.61	4	9.9	1.85	4	9.2	3.52	8	8.6
Uncoated sphere wall	–	–	–	2.58	2	3.9	4.27	2	1.2

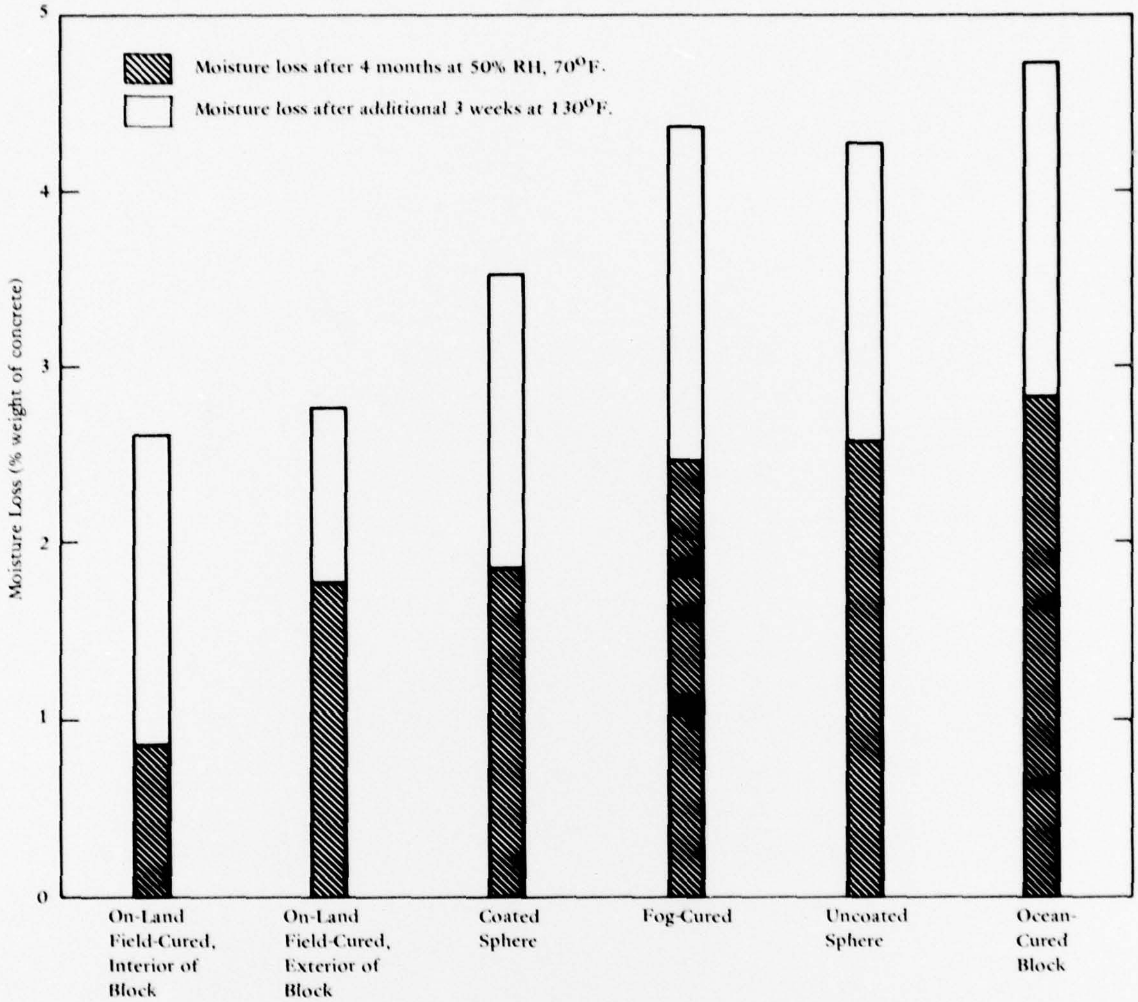

Figure C-1. Moisture content of concrete.

Appendix D

CEMENT PASTE SAMPLES PLACED IN THE OCEAN

To study the phenomenon of magnesium ions replacing calcium ions in tobormorite gel, small neat cement paste samples were mounted on the chain of Spheres no. 15 and 16 on 7 Mar 1978. Ten samples were placed, five at each sphere. The samples were 1 inch in diameter by 2 inches long (25 x 51 mm). They were suspended from a steel bar that was hooked onto the sphere chain. The samples were hung from insulated electrical cables about 1.5 feet (0.5 m) below the bar. Each cable contained a plug-in type connector (Figure D-1). In the future to retrieve a sample, a submersible can use its manipulators to disconnect the plug.

The cement paste samples were prepared on 1 Jan 1978 by Professor P. K. Mehta of the University of California at Berkeley. The paste was made of Type II Portland cement having a water-to-cement ratio of 0.60. The relatively high water-to-cement ratio was used to create a higher-than-normal porosity. The samples were made using a technique that prevented bleeding.

The chemical composition for the cement is given in Table D-1. Comparison samples to those in the ocean were placed in a fog room environment at CEL and the University of California at Berkeley.

Table D-1. Chemical Composition of Portland Cement

Chemical	Percent
SiO_2	22.36
Al_2O_3	3.75
Fe_2O_3	2.10
CaO	65.89
MgO	1.77
SO_3	2.29
C_3S	63.5
C_2S	16.3
C_3A	6.4
C_4AF	6.4
Blaine, cm^2/g	4,800

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Figure D-1. Arrangement for suspending cement samples from chain of Spheres no. 15 and 16.

Appendix E

MICROSTRUCTURE EXAMINATION OF CONCRETE

by
Prof. P. K. Mehta
University of California, Berkeley

The results of a microstructure examination of the concrete samples listed in Table E-1 are summarized below.

Aggregate pieces from the concrete were carefully separated as much as possible before crushing and grinding the remainder of the sample for x-ray diffraction analysis. All x-ray diffraction analysis work was conducted at 40 kV, 35 mA Cu kα.

There was no evidence of unhydrated cement compounds in any of the specimens. This showed that the cement was more or less completely hydrated. All the samples showed substantial amounts of calcium hydroxide, thus indicating that the hardened cement pastes were undamaged in every case. Since large peaks due to quartz and feldspar emanating from sand were also present, it was not possible to make any estimate of the relative quantities of calcium hydroxide in the different specimens. Concrete samples no. A, B, and C showed small peaks due to ettringite. In no case were peaks large enough to draw any conclusions. Concrete sample no. A (piece from wall of sphere no. 12) differed only in one respect from the others. It showed two small peaks, 2.54 A and 2.16 A, which are possibly due to the presence of calcium carboalumi-nate hydrates. However, these peaks are not very large, and all major peaks due to carboaluminate hydrates were not present. Therefore, it is concluded that the concrete has remained essentially unaltered.

Table E-1. Concrete Samples for Microstructure Examination

Sample No.	Sample Description	Curing History
A	Piece of uncoated wall from hemisphere W-32, which was part of Sphere no. 12.	5.3 yr at 2,790 ft in the ocean
B	Piece of concrete block that was attached to Sphere no. 12. Concrete was from same batch as that of hemisphere W-32.	5.3 yr at 2,790 ft in the ocean
C	Piece of control cylinder that corresponded to hemisphere W-32.	Fog curing, 100% RH, 73^{o}F for 5.6 yr
D	Piece of concrete block that remained exposed to on-land field conditions. Concrete was from same batch as that of hemisphere W-29 (other hemisphere to Sphere no. 12).	Field-cured on land, 150 ft from ocean for 5.6 yr
E	Piece of coated wall from hemisphere W-26, which was part of Sphere no. 13.	5.3 yr at 2,635 ft in the ocean

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